# Upper Limb Movement Modelling for Adaptive and Personalised Physical Rehabilitation in Virtual Reality

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*I confirm that the word count of this thesis is less than 100,000 words*

*I want to dedicate this thesis to all those who are living with a stroke.*

*"Our greatest glory is not in never falling,*

*but in getting up every time we fall."*

*Confucius*

# CONTENTS

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# ABSTRACT

Stroke is one of the leading causes of disability with over three-quarters of patients experiencing an upper limb impairment varying in severity. Early, intense, and frequent physical rehabilitation is important for quicker recovery of the upper limbs and the prevention of further deterioration of their upper limb impairment. Rehabilitation begins almost immediately at the hospital. Once released from the hospital it is intended that patients continue their rehabilitation program at home supported by a community stroke team. However, there are two main barriers to rehabilitation continuing effectively at this stage. The first is limited contact with a physiotherapist or occupational therapist to guide and support an intensive rehabilitation programme. The second is that conventional rehabilitation is tough to maintain immediately after stroke due to fatigue, lack of concentration, depression and other effects. Stroke patients can find exercises monotonous and tiring, and a lack of motivation can result in patients failing to engage fully with their treatment. Lack of participation in prescribed rehabilitation exercises may affect recovery or cause deterioration of mobility.

This thesis examines the hypothesis that upper limb stroke rehabilitation can be made more accessible and enjoyable through the use of modern commercial virtual reality (VR) hardware, with personalised models of user hand motion adapted to user capability over time, and VR games with tasks that utilise natural hand gestures as input controls to execute personalised physical rehabilitation exercises. To support the investigation of this hypothesis a novel adaptive, game-based, virtual reality (VR) rehabilitation system has been designed and developed for self-managed rehabilitation. Hands are tracked using a Leap Motion Controller, with hand movements and gestures used as in input controller for VR tasks. A user-centred design methodology was adopted, and the final version of the system was evolved through several versions and iterative testing and feedback through trials with able-bodied testers, stroke survivor volunteers, and practising clinicians.

A key finding of the research was that an adapted form of Fitts's law, that models difficulty of reaching and touching objects in 3D interaction spaces, could be used to profile movement capability for able-bodied people and stroke patients

in upper arm VR stroke rehabilitation. It was also found that even when Fitts's law was less effective, that the statistics of the regression quality were still informative in profiling users. Fitts law regression statistics along with information on task performance (such as percentage of hits) could be used to adapt task difficulty or advising rest. Further, it was found that multiple regression could provide better movement capability profiles with a modified form of Fitts law to account for varying degrees of difficulty due to the angles of motion in 3D space. In addition, a novel approach was developed which profiled sectors of the 3D VR interaction space separately, rather than treat movement through the whole space as being equally difficult. This approach accounts for some stroke patients having more difficulty moving in some directions than others, e.g. up and left. Results demonstrate that this has potential but may need to be investigated further with stroke patients and with larger numbers of people.

The VR system that utilised the movement capability model was evolved over time with a user-centred design methodology, with input from able-bodied people, stroke patients, and clinicians. A final longitudinal study investigated the suitability of three bespoke games, the usability of the system over a longer time, and the effectiveness of the movement profiler and adaptive system. Throughout this experiment, the system provided informative user movement profile variations that could identify unique movement behaviour traits in individuals. Results showed that user performance varied over time and the adaptive system proved effective in changing the difficulty of the tasks for individuals over multiple sessions. The VR rehabilitation games incorporated enhanced gameplay and feedback, and users expressed enjoyment with the interactive experience. Throughout all of the experiments, users enjoyed wearing a VR headset, preferring it over a standard PC monitor. Most users subjectively felt that they were more effective in completing tasks within VR, and results from experiments provided empirical evidence to support this view. Results within this thesis support the proposal that an appropriately designed, adaptive game-based VR system can provide an accessible, personalised and enjoyable rehabilitation system that can motivate more regular rehabilitation participation and promote improved motor function.

# LIST OF ABBREVIATIONS AND ACRONYMS

1D – One Dimensional

2D – Two Dimensional

3D – Three Dimensional

VR – Virtual Reality

VE – Virtual Environment

UI – User Interface

SUS – System Usability Scale

OS – Overshoot

AAROM – Active Assistive Range of Motion

CIMT – Constraint-Induced Movement Therapy

ADL – Activities of Daily Living

ARAT – Action Research Arm Test

BB – Box and Block Test

CAHAI – Chedoke Arm and Hand Activity Inventory

JHFT – Jebsene Taylor Hand Function Test

WMFT – Wolf Motor Function Test

MAL – Motor Activity Log

SIS – Stroke Impact Scale

CPSP – Central Post-Stroke Pain

CSF – Cerebrospinal Fluid

# LIST OF TABLES

# List of Figures

# LIST OF APPENDICES

# Note on Access to Content

# 1 INTRODUCTION

## 1.1 STROKE

A stroke is generally caused when the blood supply carrying essential nutrients and oxygen to the brain is cut off, damaging or killing brain cells. This damage to the brain can have several different effects depending on where the damage has occurred, impacting the way the body functions, feels, thinks and communicates (NHS Choices, 2017). There are two main types of stroke; the most common is an ischaemic stroke caused by a blockage cutting off the blood supply to the brain due to narrowing of the arteries leading to the brain. Conditions or behaviours that can accelerate an ischaemic stroke include smoking, high blood pressure, obesity, high cholesterol, diabetes and excessive alcohol intake. Another less common cause is a haemorrhagic stroke, caused by burst blood vessels resulting in bleeding in or around the brain. The main cause of a haemorrhagic stroke is high blood pressure which can weaken the arteries in the brain increasing the chances of a split or rupture of the artery (Stroke Association, 2015b).

Increasing numbers of people have been surviving a stroke, presumably due to the increasing knowledge of the condition and advancements in medical care. Currently, there are over 1.2 million stroke patients in the UK, and it is the fourth single cause of death in the UK. It is the leading cause of disability with two-thirds of people who have survived a Stroke are leaving the hospital with a disability. Stroke causes the highest range of disabilities resulting in a negative impact on the person's lifestyle (Stroke.org.uk, 2017). Limb Weakness is very common with 77% of patients reporting arm weakness and 72% reporting leg weakness. Visual Problems, Aphasia, fatigue, memory issues, depression and emotionalism, are also very common effects of a stroke, and all of these effects can an impact lifestyle, working life and independence of the person (Stroke.org.uk, 2016).

# 1.2 STROKE PHYSICAL REHABILITATION

Many people are left with varying degrees of physical impairment following a stroke; it is vital that a person with an onset stroke, who is medically stable, receives frequent, short daily mobilisation during their time in hospital. Early mobilisation aims to minimise the risk of the complications of immobility and improve functional recovery quicker. Typical mobilisation will begin 24 to 48 hours of an onset stroke (Intercollegiate Stroke Working Party, 2016). After an onset stroke, some people recover rapidly and completely, while others continue to have physical impairments persisting over weeks, months even years. In some cases, a person's impairments can deteriorate as the person's recovery priorities change, e.g. for most stroke patients, they tend to prioritise the rehabilitation of their legs before their upper limbs, so they can walk and get around without others. Early rehabilitation of physical impairments is vital in the first months after stroke to increase the chances of a rapid recovery.

During rehabilitation, patients are cared for by several specialists, trained to help stroke patients for a range of disabilities after a stroke. Physiotherapists (PT) and occupational therapists (OT) focus mainly on the recovery of the person's physical impairments on a one to one basis. Physiotherapists are concerned with restoring a person's functional movement, by helping the person learn to use their paretic limbs again through exercise, manipulation, massage and electrical treatments. These treatments help regain muscle control and strength in the paretic limbs as much as possible. Occupational therapists focus on evaluating, managing and improving functional abilities that the person often uses during their daily life. They do this by assessing their strengths and weaknesses during activities of daily living (ADL), for example, dressing, making dinner, or brushing their teeth. Occupational therapists devise compensatory and practical movement solutions to manage and improve a person's independence, and they tend to experiment with different techniques, equipment or change the person's environment if it could help (OTA, 2017).

After an initial assessment of the stroke patient's movement skills, physiotherapists and occupational therapists design a rehabilitation plan tailored to the individual. Part of this program is setting rehabilitation goals to monitor the person's progress towards recovery. Effective goal setting should include family and carers wherever possible; goals should be meaningful, challenging and have personal value to the person. Goals should be assigned a timeframe, depending on the person's condition these goals can be short-term, long-term or both. As rehabilitation continues, therapists may change or adapt a person's current goals depending on their continued assessment of the person's condition (Hurn, Kneebone and Cropley, 2006; Intercollegiate Stroke Working Party, 2016). Meeting these goals usually require intensified rehabilitation; typical guidelines suggest that the person should ideally receive a minimum of 45 minutes of each rehabilitation therapy for a minimum of five days per week for people with an ability to do so (NICE, 2013). People who are considered unable to participate for this required time are still recommended to participate in rehabilitation for five days a week, but for a shorter time at an intensity that enables the person the actively engage with rehabilitation. Rehabilitation exercises and tasks during therapy sessions are typically performed in numbers of repetitions (repetitive task training) with the extent of repetitions being adapted by the PT or OT, based on aspects including but not limited to motor capacity, stamina, concentration levels or fatigue. Repetitive exercise facilitates the re-wiring of the brain, creating new neurological pathways in parts of the undamaged brain, this is known as neuroplasticity which refers to the process of the brain's ability to reorganise neurons, allowing the brain to heal parts of the body (McBean and Wijck, 2013a).

### 1.2.1 UPPER LIMB REHABILITATION

Upper limb impairment after a stroke is a very common effect with over three-quarters of people experiencing some level of arm impairment. Common symptoms associated with upper limb impairment include paresis, loss of fractionated movement, abnormal muscle tone and spasticity (McBean and Wijck, 2013b). These impairments can occur in segregation, but it is not unusual that they occur in union as they are caused by damage to the same neurological structure in the brain. Paresis is the decreased or absent ability to voluntarily move a muscle or muscle groups. Fractionated movement is the ability for muscles to act independently of other muscles, loss of fractionated movement can severely affect upper limb function; for example, a deficiency in fractionated movement can result in failure to move fingers separately to point or grasp objects; useful for many activities of daily living. Muscle tone is the amount of resistance provided by the muscles when resting or stretching; normal muscle tone helps maintain correct posture and contractions. Abnormal muscle tone is an increased or decreased resistance in muscle tone. These may be categorised by two symptoms, hypotonia (low tone) and hypertonia (high tone). Hypotonia is a decrease in muscle tone resulting in the muscles unable to fully contract remaining loose and slack give a "floppy" appearance. Hypertonia is the opposite when too much muscle tone has developed in the limbs resulting in the limb becoming stiff and difficult to move (Lang *et al.*, 2013). Spasticity is defined as increased resistance to sudden passive movement, and it is velocity dependent. The faster the passive movement, the stronger the resistance from the limb. Spasticity can be characterised as tight and stiff muscles, making it difficult for the person to control coordination. The severity of spasticity can increase over time if not treated or managed, causing hyperactive reflexes, which is the over responding to stimuli, causing exaggerated reflexes. This is usually witnessed in people with joints and limbs that have a specific fixed pose, for example, the arm rested across the chest or fingers in a fist-like gesture.

The focus of rehabilitation of the paretic upper limbs is to relearn specific motor skills to support fuller engagement with ADLs and to reduce the reliance on others to help and gives the person increased independence. After the patient's upper limbs have been assessed and rehabilitation goals have been set for the patient. A physiotherapist and occupational therapist will devise a personalised rehabilitation program to help the recovery of the patient's upper limb motor skills. If a therapist identifies movement limitations, they will usually offer repetitive task training. Usually, the training involves reaching, grasping, manipulation, releasing and daily task-specific activities such as lifting a cup. *Reaching* – to lengthen the arm out toward a specific location to touch or grasp something; locations can be at various distances and heights to target specific arm movements. *Grasping and manipulation* – the aim of touching and holding on to an object using fingers and wrist. Object size and shape can vary to improve grasp strength, precision and size. Typically, when grasping is performed the person is usually asked to traverse the grasped object to a different location and *release* the object. The paretic upper limb can be exercised separately, although most ADLs require both limbs to move in unison, either in symmetrical or bimanual actions such as pouring water into a glass from a jug. Many ADLs require reaching motion towards objects before they can be grasped, or manipulated, PTs and OTs will generally start with reaching to grasping exercises or tasks for the person to perform their ADLs (Stroke Association, 2009). Many training exercises are used for upper limb rehabilitation; some common exercises include:

a) *Passive Range of Motion* – is a method of an external force applied to the paretic arm to move. An example would be a patient using their stronger arm to move their weaker arm; machines are another possible way to use a passive range of motion. These exercises help maintain joint flexibility and prevent joint contracture.
b) *Active Assistive Range of Motion (*AAROM*)* – this range of movement training is where the weak limb is assisted to movement. The weak limb can perform the movements required to a certain degree on its own but required assistance to complete the movement. AAROM helps strengthen the weak limb that does not yet have a full range of motion.
c) *Strengthening or Resistance Training* – rehabilitation exercises often consist of strength exercises that involve moving the weaker limb against resistance typically using resistance rubber bands and weights. These types of exercises will progressively overload muscles, so they become stronger.
d) *Stretching Exercises* – Often in people with a stroke, their muscles in the weak arm can become tight. Regular stretching prevents joint stiffness and the shortening of muscles.
e) *Constraint Induced Movement Therapy* (CIMT) – attempts to improve the paretic arm using intensive training tasks while preventing the use of the stronger arm. This attempts to change the behaviour of the person who may form a habit of using both arms instead of one, thus helping to reduce neglect of the weaker arm (Figure 1-1).

**Figure 1-1: A stroke patient performing Constraint Induced Movement Therapy**

### 1.2.1.1 ASSESSMENTS OF UPPER LIMB MOTOR SKILLS

There are many different assessment tools to measure and identify multiple effects after a stroke, including paresis, fractionated movement, or muscle tone. The assessment tools chosen to assess a patient are usually at the preference of the PT or OT, and no one tool can capture all upper limb functional activities. The outcome measures influence the decisions towards devising rehabilitation goals and interventions. Assessments should be performed on a regular basis with the same measure administered throughout, to monitor recovery progress or the lack thereof. This could lead to changes or modifications to rehabilitation goals and interventions. Some of the cited and validated assessment tools that measure upper extremity (UE) motor function are seen below:

a) *Action Research Arm Test (ARAT)* – a 19 item measure which is divided into four subscales, gross arm movement, grasp, grip and pinch. Performance on each is rated on a 0-3 point scale. The assessment starts with the most difficult tasks first. A score of 3 signifies that the item was performed with normal movement performance and the remaining subscale are also given a score of 3. If a movement cannot be performed (score of 0), then the remaining items in the subscale are skipped. There is a maximum score of 57, a score close to the maximum suggests close to the normal movement was performed.
b) *Box and Block Test (BB)* – the person is seated in front of a rectangle box with two equal sized compartments divided by a partition. Small blocks are placed in the compartment on the side of the paretic arm. The individual is asked to grasp, transport and release the blocks over the partition into the

other compartment. The number of blocks moved in one minute provides a measure of performance. A higher number of blocks indicates a better gross manual dexterity.

c) *Chedoke Arm and Hand Activity Inventory (CAHAI)* – is a performance test using functional items, designed to encourage bilateral function rather than assess the person’s ability to complete the tasks. There are 13 functional tasks such as opening a jar, drawing a line with a ruler, placing toothpaste on a toothbrush, and zipping up a zipper.

d) *Jebsene Taylor Hand Function Test (JHFT)* – is designed to assess uni-manual hand functions commonly used for ADLs. JHFT includes seven subtests, writing a sentence, card turning, picking up and placing small common objects, stacking checkers, stimulated feeding, moving light and heavy objects. Both hands perform each subtest separately beginning with the non-dominant hand. Each subtest is scored based on the time taken to complete the task with a maximum of two minutes allotted for each subtest. A lower score suggests greater hand function mainly assessing the speed of the hand function rather than the quality of the hand's function.

e) *Nine Hole Peg Test* – individuals, are asked to pinch and pick up pegs, one by one and place them into holes on a board as quickly as possible. Once all nine pegs are placed in the holes, they then remove the pegs placing them back into the container. The score is determined by the time taken to complete the task. Quicker times suggest better finger dexterity.

f) *Wolf Motor Function Test (WMFT)* – consists of 15 items of UE measurements, the first six tasks are timed functional tasks, and items seven to 15 are strength tasks. For each task, a time and functional ability score (FAS) is recorded on a six-point scale (0-6). A FAS of 0 denotes that the person was unable to complete the task and a score of 6 indicates that the task was performed with normal movement. A higher recorded average time and FAS of the individual items shows better performance. The WMFT assessment aims to measure dexterity, strength and UE function.

g) *Motor Activity Log (MAL)* – is a semi-structured interview to assess arm function. Individuals are asked to rate Quality of Movement (QOM) and amount of Movement (AOM) during 30 daily functional tasks. Tasks include using objects such as a pen, fork, comb and cup for ADLs. Other tasks include the use of the arm during gross motor activities (e.g. steadying him/her during standing, pulling a chair into a table). Each task is scored on a six-point scale; a zero score indicates that the weaker arm was never used and a score of five suggests the person felt that they had normal usage of their weaker arm.

h) *Stroke Impact Scale (SIS)* – is another self-reporting tool; it is a 59 item measure. For each item, the individual is asked to rate the level of difficulty of the item over the past two weeks. The 59 item separated into eight domains, Strength, Hand Function, ADLs, Mobility, Communication, Emotion, Memory,Thinking and Participation/Role function. Each item is assessed on a five-point Likert scale, 1 indicates that the individual could not do it at all and five not difficult at all.

### 1.2.1.2 THE EFFECTS OF A STROKE

Upper limb weakness after a stroke affects 77% of people in the UK. It is not uncommon that other side effects of a stroke can occur in conjunction. Multiple side effects can complicate a person's life and reduce independence. When designing technology for a stroke patient, some of these side effects need to be considered for better usability and engaging experience. Common side effects include:

**VISUAL FIELD LOSS**

The visual field explains the whole area of the human vision including the central and peripheral vision. Vision loss can occur in the central or outer portions of the visual field. That is, a person is unable to see to the left or right from the centre of their field of vision in both eyes. After a person has a stroke to one side of the brain, that person may develop vision loss to the opposite side. The degree of vision loss can vary depending on the severity of the stroke. Reading can be a very frustrating experience because the start and end of sentences could be missed. Scanning techniques (eye movement patterns) can be used to help compensate for vision loss. For example, practising scanning by keeping the head still and moving the eyes around a room to the affected side of vision (Figure 1-2).

**Figure 1-2: Left side vision lost –an estimate of what a person might see but is not exactly what the person sees.**

## VISUAL NEGLECT

Visual neglect is the incapacity of a person to see objects on one side, caused by the way information is processed in the brain. Suffering from visual neglect it may be possible that when eating food, a person may ignore one half of the plate that the neglect is affected or collide with the environment on the neglected side. Treatments for visual neglect include the use of prisms, but most often scanning techniques are used as a coping mechanism. If visual field loss and visual neglect both occur, scanning techniques are less likely to be effective in helping compensate for visual neglect.

## EYE MOVEMENT PROBLEMS

A stroke can lead to eye movement problems causing the failure of the eyes to move in synchronous. Blurry vision, double vision, depth perception and nystagmus (eye wobbling) are eye movement problems seen post-stroke. Reading, walking and ADLs become difficult to perform, there are various treatments used to regain focus and improve eye movement. Eye exercises or wearing prisms (optical devices placed on spectacles) are possible ways to correct movement problems. An eye patch is sometimes worn to improve double vision but can have adverse effect causing depth perception.

**APHASIA**

Aphasia is a language and communication disorder affecting a person's speech, reading, writing, understanding. After a stroke, a person may still think in the same way but are unable to communicate their thoughts easily due to aphasia. People are affected differently by aphasia, rarely seeing the same degree of difficulties in others (Stroke Association, 2015a).

**MEMORY**

Most people experience memory loss at a time, and this often increases with age. Around 33% of people experience memory loss after a stroke. Types of memory loss that may be experienced are memory loss in verbal conversations and vascular dementia (incapacity to think). People may have problems with short-term memory, getting lost in familiar places or difficulty following instructions. Treatment involves brain retraining techniques designed to improve thinking and memory. Training can be done with or without computer applications. Sometimes physical exercise can improve physical and mental health also trying a new activity or hobby that involves the mind and body can help. Managing memory such as using memory cues, having a routine and repetition of actions and asking others to repeat things can help compensate for memory loss (National Stroke Association, 2014).

**PAIN**

Post-stroke, various painful conditions can occur such as spasticity and shoulder pain, headaches and swollen hands. Pain can persist for prolonged periods of time with medication and physiotherapy successfully relieving the pain. Pain management clinics and coping techniques are other such treatments used to manage long-term pain. The following are some common conditions causing pain:

a) *Spasticity* - can cause muscles to tense and contract abnormally causing spasm which can be very painful. Treatments include physiotherapy, medication and Botox.
b) *Shoulder pain* - is common after a stroke; there are different types of shoulder pain. Frozen shoulder – your shoulder becomes stiff, and it hurts to move it, subluxation – is where the arm has become partially dislocated. Usually due to the muscles attaching the arm and shoulder both become weak. Prevention of shoulder pain involves health professionals making

sure that the strain on the shoulder joint is minimised. Correct positioning reduces strain on ligaments, helping to prevent frozen shoulder. Foam support or pillows can be used to make sure the shoulder is in the correct position. Overhead arms slings should not be used as there is insufficient evidence that they help shoulder pain.

c) *Central post-stroke pain (CPSP)* - is also known as Dejerine-Roussy syndrome or central pain syndrome. Mainly people describe the pain as an icy burning sensation or a throbbing or shooting pain. Some people also experience pins and needles or numbness in the area where the pain is felt. It can affect large portions of the body or specific regions such as hands or feet. CPSP may become worse in some people because of movements, emotion or temperature change (usually cold temperatures). Treating CPSP is difficult as treatment may differ depending on the neurological damage, with pain medication being the most often used treatment to reduce pain (Center, 2017; Stroke association, 2018).

d) *Headaches* - Getting headaches may be the same as before a stroke such as stress, depression, or lack of sleep. After a stroke, headaches may be a direct effect of a stroke if there is swelling of the brain. Fluctuation in the levels of cerebrospinal fluid (CSF) can cause headaches. Pain from headaches should lessen over time and is typically controlled by painkillers (Stroke association, 2018).

e) *Swollen hand* - After a stroke, the person’s hand may swell and become painful; this usually happens when the hand is not moving a lot maybe due to paresis. Treating this pain, it is best to elevate the hand or to get the hand moving again with the help of a physiotherapist.

**FATIGUE**

It is natural for a person to become fatigued occasionally due to lack of sleep or having had a busy day. Typically, after a period of rest fatigue will have a reduced impact on your body and mind. Post-stroke, fatigue happens differently. It can arrive suddenly, and rest may not always reduce the effects of fatigue. There is no specific treatment for post-stroke fatigue but managing fatigue can help reduce the impact of fatigue on daily activities. Fatigue management guidelines (Stroke Association, 2018) include:

a) Taking plenty of time to improve your condition can help you cope better. It may take several months before post-stroke fatigue may subside or reduce.
b) Keeping a diary of your progress, as time passes this may show improvements you have made.
c) Don't push yourself too much if you're having a good day; it can have adverse effects for the next coming days.
d) Learn to pace yourself by taking appropriate breaks before and after activities.
e) Listen to your body; rest if you feel exhausted.
f) Work out how much you can do in a day and keep to it.
g) Build up stamina and strength slowly by increasing activity gradually.
h) Try to maintain some level of exercise as regular exercise may help to improve fatigue.
i) Eating healthy foods that are useful sources of energy such as carbohydrates, fruit and vegetables.

Stroke patients can experience a different range of effects caused by stroke and at various levels of severity. It is challenging to design a VR rehabilitation system that accounts for all these side effects and varying levels of severity. This impacts the design of rehabilitation exercises, user interface (UI), interactions, and virtual environments (VE) that are suitable for everyone individually. Thus, the usability of a VR rehabilitation system is also impacted, which is an important factor in the acceptability and accessibility of a stroke rehabilitation system for stroke patients.

# 1.3 THE POTENTIAL BENEFITS OF VR REHABILITATION

Conventional upper limb stroke rehabilitation exercises have been effective in maintaining and improving functional upper limb mobility and ADLs. However, one limitation of conventional rehabilitation is that stroke patients tend to find exercises monotonous and tiring. Motivation to perform the exercises can be impacted causing a lack of engagement in their rehabilitation program. Therefore, the person usually becomes complacent in their frequency and intensity of their rehabilitation exercises, or they stop altogether. This can have an impact on their functional recovery resulting in no improvements or in some cases deterioration in their upper limb mobility. Considerable research has been undertaken over the last two decades investigating how Virtual Reality (VR) and gaming technology can increase engagement and motivation in stroke rehabilitation, so stroke survivor stays interested in rehabilitation. There is sufficient evidence that these VR and gaming technologies provide engaging and motivational factors (Webster and Celik, 2014; Levin, Weiss and Keshner, 2015; McNulty *et al.*, 2015) with significant potential to support self-management of rehabilitation exercise programs, in that it allows individuals to interact and train within interesting, realistic virtual environments. It provides users with the opportunity to practice intensive repetition of meaningful task-related activities necessary for effective rehabilitation (Crosbie *et al.*, 2007). A recent Cochrane review of 72 trials involving 2470 participants for the upper limb, stated that the use of VR and gaming might be beneficial in improving upper limb function and ADLs as conventional therapy; when used as an adjunct to usual care or when compared with the same dose of conventional therapy (Laver *et al.*, 2017). However, they emphasized the need for pilot studies assessing usability and validity as part of the development process if designing new VR programs for rehabilitation purposes; these studies may also afford insight on the key VR characteristics for retraining of movement, e.g. in reach and pointing tasks. VR systems are flexible technologies supporting feedback, capability adaptation, high intensity, repetitive functional exercises to encourage motor control and motor learning. There is an increasing number of studies that are particularly focused on using commercially available hardware devices to support upper limb rehabilitation (Laver *et al.*, 2015). Recent advancements in commercially available VR and gaming hardware in the last few years has given more potential for new, more flexible and inexpensive rehabilitation technology solutions. New hardware technologies such as the Leap Motion Controller and Myo Armband; along with existing technologies has the potential to improve accuracy and reliability of performance monitoring as well as provide an easy to use VR rehabilitation solution. However, research is limited in these technologies and needs further investigation into the benefits intended for stroke rehabilitation. A user interface (UI) is one of the most important aspects of any VR or gaming experience. A UI provides access through various methods of interactions to the mechanisms and information within VR and games. Methods of interaction can vary from a mouse to motion trackers such as the Kinect and even speech devices such as Amazon's Alexa. A Powerful VR and gaming system with a poorly designed UI can have a negative impact on usability. An important factor of usability from a rehabilitation perspective is the capability of the system to adapt to a diversity of motor skills over time for all individuals (Burke *et al.*, 2009). Adaptation is important as a user may become frustrated if the tasks are too difficult or bored if tasks are too easy; thus, maintaining engagement which is vital in rehabilitation.

## 1.4 RESEARCH AIM AND OBJECTIVES

The overall aim of the research outlined in this thesis was to design and develop a novel virtual reality (VR) based upper limb rehabilitation system using state-of-the-art headsets and high precision hand and finger sensors and investigate its usability and applicability to stroke patients.

The main objectives of the research were:

1) *Literature Review*: Conduct a review of commercial state-of-the-art technologies and rehabilitation in practice, virtual reality-based stroke rehabilitation research, and best practice user interface design.
2) *Design Guidance Framework*: Develop a list of requirements, constraints, and caveats from the literature and in collaboration with academic and practising clinicians. Feedback from stroke patients is also required to be

gathered to determine design factors related to the patient condition. Game design and gamification of rehabilitation exercises are also considered and how they promote a positive behaviour change in stroke patients to adhere to and engage in rehabilitation.

3) *User Centred System Design, Development, and Testing*: Create a fully operational VR rehabilitation system with built-in user movement, strength calibration, and several games which uses a user profiling system to personalise gameplay within several adaptive VR rehabilitation games. Utilise a User Centred Design approach to evolve the system design through iterative design, development and testing of the system.
4) *User Movement Profiling*: Using data analysis techniques investigate the use of Fitts's law to model user arm movement in reach and touch tasks within the VR user interface. Test and evaluate this approach with first healthy users and then impaired users as the basis of user motion profiling and for adaptive difficulty setting.
5) *Usability Evaluation*: Evaluate the usability of the VR system with both healthy and impaired users.

### 1.4.1 THESIS CONTRIBUTIONS

The main contributions of this thesis are:

**Contribution A).** The creation of a design tool for designing and evaluating gamified rehabilitation applications that encompass different types of users and how they are motivated, to change a person's behaviour from a potentially harmful behaviour to a positive behaviour towards rehabilitation exercises to promote adherence to rehabilitation. Using the design tool for evaluation purposes, the evaluation of commercial games and popular rehabilitation gaming system found that rehabilitation gaming systems primarily focused on achievement-based gameplay (Holmes *et al.*, 2015; Boureaud *et al.*, 2016).

**Contribution B).** The design and development of an adaptive VR game-based rehabilitation system with state-of-the-art virtual reality hardware and sensor technologies for natural user interface control; using hand movement and finger gestures as a controller.

**Contribution C).** The creation of a unique user movement model based on Fitts Law to profile an individual's movement characteristics (D. E. Holmes *et al.*, 2016; D. Holmes *et al.*, 2016).

a. The model identified user movement behaviours, learning effects, and fatigue observed in the user's movement over-time with upper limb impaired and able-bodied users.
b. The user movement model could identify strengths and weakness in the user's range of movement per movement zone, initially with able-bodied users.
c. The user model showed a larger diversity between impaired patients and able-bodied users.

**Contribution D).** The development of an adaptive VR rehabilitation gaming system using a custom-designed algorithm to dynamically adjust the difficulty of reach and touch tasks based on the unique user movement model developed. Novel sub-parts to this system include:

a. Identifying learning phases and poor movement performance over multiple sessions.
b. Adapted to the movement performance of an individual between sessions to provide the right level of difficulty of each game for the individual to practise and improve movement coordination.
c. The adaptive system was capable of outputting high-level performance feedback about the user's movement regarding speed, accuracy and consistency although the understanding of this information had mixed results.

**Contribution E).** The discovery of design considerations for using VR in upper limb stroke rehabilitation including:

a. An initial calibration of the user movement to personalise the game environment more appropriately.
b. VR headsets promote enjoyment and improve user movement performance.
c. Visual and tactile cues promote improved target acquisition for reach and touching exercises.

d. Prolonged use of VR hardware can cause discomfort due to the increasing temperature of the hardware. Shorter sessions using the VR hardware would be recommended.
e. The increased temperature of the hardware reduces the quality of tracking by the Leap Motion Controller; shorter sessions would also help maintain optimal tracking.

## 1.4.2 RESEARCH PUBLICATIONS

### 1.4.2.1 PEER REVIEWED CONFERENCE PAPERS

**Holmes DE**., Charles, DK., Morrow, PJ., McClean, S. and McDonough, S. 2016 *Usability and performance of Leap Motion and Oculus Rift for upper arm virtual reality stroke rehabilitation*, Los Angeles USA, International Conference of Disability, Virtual Reality & Associated Technologies, pp. 1-10.

**Holmes DE**., Charles, DK., Morrow, PJ., McClean, S. and McDonough, S. 2015 *Rehabilitation Game Model for Personalised Exercise*, Nottingham UK, Interactive Technologies and Games for Education, Health and Disability, pp.1-8.

**Dominic E Holmes**, Darryl K Charles, Philip J Morrow, Sally McClean, and Suzanne M McDonough, "*Usability and Performance of Leap Motion and Oculus Rift for Upper Arm Virtual Reality Stroke Rehabilitation*", Journal of Alternative Medicine Research, 2017;9(4).

**D E Holmes**, D K Charles, S McClean, P J Morrow, S M McDonough, "Using Fitts's Law to Model Arm Motion Tracked in 3D by a Leap Motion Controller for Virtual Reality Upper Arm Stroke Rehabilitation", IEEE Computer-Based Medical Systems 2016.

S Howe, D K Charles, **D E Holmes**, I Wilson, S McDonough, 2017, "Older adults' experience of falls prevention exercise delivered using active gaming and virtual reality", Physiotherapy UK pp. 1-10.

Boureaud J., **Holmes DE**., Charles, DK., Morrow, PJ., McClean, S. and McDonough, S. 2016 *Application of a Rehabilitation Game Model to Assistive Technology Design*, Los Angeles USA, International Conference on Disability, Virtual Reality & Associated Technologies, pp. 1-4.

Chaponneau G., **Holmes, DE**., Charles, DK., Morrow, PJ., McClean, S. and McDonough, S. 2016 Application of Invisible Playground Theory to Assistive Technology Design for Motivating Exercise Within Activities of Daily Living, Los Angeles USA, International Conference on Disability, Virtual Reality & Associated Technologies, pp. 1-4.

J W McKinney, D K Charles, S M McDonough, P J Morrow, N C Kennedy, **D E Holmes**, 2018, *Reflections on the Design and Development of a Virtual Reality Mirror Therapy System for Upper Limb Stroke Rehabilitation*, International Conference of Disability, Virtual Reality & Associated Technologies, pp 1-4

### 1.4.2.2 AWARDS RECEIVED FROM THE RESEARCH PUBLICATION

**Winner of best student conference paper:** Holmes et al., 2016 "*Usability and performance of Leap Motion and Oculus Rift for upper arm virtual reality stroke rehabilitation"* at the International Conference of Disability, Virtual Reality & Associated Technologies, 2016.

**Short paper commendation:** Chaponneau G., **Holmes, DE**., Charles, DK., Morrow, PJ., McClean, S. and McDonough, S. 2016 Application of Invisible Playground Theory to Assistive Technology Design for Motivating Exercise Within Activities of Daily Living, Los Angeles USA, International Conference on Disability, Virtual Reality & Associated Technologies, pp. 1-4.

### 1.4.2.3 PODIUM PRESENTATIONS

**Holmes DE**., Charles, DK., Morrow, PJ., McClean, S. and McDonough, S. 2016 *Usability and performance of Leap Motion and Oculus Rift for upper arm virtual reality stroke rehabilitation*, Los Angeles USA, International Conference on Disability, Virtual Reality & Associated Technologies, pp. 1-10.

**Holmes DE**., Charles, DK., Morrow, PJ., McClean, S. and McDonough, S. 2015 *Rehabilitation Game Model for Personalised Exercise*, Nottingham UK, Interactive Technologies and Games for Education, Health and Disability, pp.1-8.

#### 1.4.2.4 PROJECT INVOLVEMENT

**Magic** is a pre-Commercial procurement (PCP) project funded by Horizon 2020, aimed at transforming the delivery of health care services for patients who have experienced a stroke. The research team are collaborating with Tech4Care (Italy) and miThings (Sweden) to design and develop a solution called Magic Glass. The research and the rehabilitation systems described in this thesis was the basis for Magic Glass. Appointed as a research assistant and with the responsibility of integrating Ulster University's research into a commercial platform. The project has been accepted for phase 1,2 and 3 funding. It was possible also to pivot the research in pain management with the **Relief** project and has currently have been accepted for phases 1 and 2 funding.

## 1.5 THESIS STRUCTURE

This thesis contains eight chapters in addition to the introduction. Below is a summary of the contents of each chapter:

**Chapter 2:** reviews the literature for stroke rehabilitation, in particular, current technology that has the potential for stroke rehabilitation, the state-of-the-art and the foundation of VR and games research is reviewed along with existing rehabilitation systems currently being used. A literature review was conducted of existing adaptive techniques and their advantages and disadvantages. The findings from this review highlighted that the latest research on natural user interface technologies has significant potential for stroke rehabilitation despite the limited research with impaired users. A search of the literature found a number of different difficulty adaptation algorithms. A review showed difficulty adjustment is currently one of the biggest challenges for stroke rehabilitation, and current research is limited in studies with impaired users. The results of this review support the rationale for additional research.

**Chapter 3:** describes the research method used to investigate the application of VR as an assistive rehabilitation technology for upper limb impaired users following a stroke. The process of user involvement and its importance throughout the design process is discussed. A proposed approach to developing and designing games for different types of users and their motivations called the Rehabilitation Gaming Model (RGM) is explained.

**Chapter 4:** details the design and development of a virtual reality (VR) upper limb rehabilitation system based on state of the art research, called the Target Acquisition Exerciser (TAGER). The chapter explains in depth the technology architecture including the hardware and software used along with the user interface for capturing user movement data based on Fitts Law.

**Chapter 5:** reports on the main findings from the first experiment with able-bodied users to evaluate TAGER's usability and assess the capability of a user model for quantifying and profiling each user's movement towards the adaptation of task difficulty. The experiment protocol is outlined including the participant recruitment and the experimental design. Twenty-six able-bodied participants were recruited to take part in a single use experiment with TAGER.

**Chapter 6:** describes the results of TAGER with five upper limb impaired participants. The usability of TAGER and its capability to model upper limb impaired user movement for adapting task difficulty. Design considerations are explained by the changes made to the TAGER based on stakeholder feedback and results from the previous experiment to increase usability for impaired users. Comparison between the upper limb impaired participants and able-bodied users from the previous experiment are also made.

**Chapter 7:** discusses the design and development of an evolved version of TAGER to incorporate VR gaming rehabilitation system, called RESTEM, based on results from TAGER that includes refinements and redesigns to system features and the addition of games in rehabilitation. Each rehabilitation feature and game are described, and the design and development of an adaptive algorithm are also developed ready for experiments with able-bodied participants, to test the capability for the algorithm to adapt task difficulty before experiments with impaired users.

**Chapter 8:** reports on the main findings from the third and final experiment with able-bodied users to evaluate RESTEM's ability to measure user movement capability in a longitudinal study and examines the usability of the system and general system reliability before conducting a future study with upper limb impaired participants. Six participants were recruited to use RESTEM for five weeks, two sessions a week to analysis the adaptive algorithm.

**Chapter 9:** concludes the thesis and summaries the main findings of the research, showing how each research objective was reached and the potential for future research in this area.

# 2 LITERATURE REVIEW

The Health Technology industry continues to grow at a rapid pace with novel innovations and improvements in technology released every year. These innovations have the potential to impact people's lives for the better, whether it is for work or leisure. Areas which have seen the most growth include improved connected-health and cloud-based health service solutions, smart-home assistive technologies, and related internet of things (IoT) devices for tracking user movement and physiological statistics (Deloitte, 2015). New and emerging technologies have increased the viability of the quantifiable self (Quantified-Self and Institute, 2017), and enhancement support for home-based health solutions. Emerging technologies have the potential to enhance existing care pathways, facilitating increasingly early release from the hospital and supporting ongoing and effective health care. Over the past decade, there have also been significant advances in commercial products that may be used to support stroke rehabilitation. Recently released, novel technology provides improved accessibility and applicability to assisting the rehabilitation of stroke patients, such as the Leap Motion Controller (*Leap Motion, USA 2012*), HTC Vive (*HTC, USA 2016*), and Oculus CV1 (*Facebook, USA 2016*). In particular, virtual reality (VR) and associated gaming technologies have demonstrated new possibilities for enhancing existing rehabilitation practice, such as socialising with others (Ballester, Badia and Verschure, 2012), providing more automated and personalised rehabilitation in the home (Johnson, 2016), having the potential to adapting (Burke *et al.*, 2009; Dowling *et al.*, 2014; Karime *et al.*, 2014; D. E. Holmes *et al.*, 2016) to patients' rehabilitation based on their health, movement capability and performance, inclusion of multiple therapy types, and encouraging adherence (Jordan *et al.*, 2010; Perez-Marcos *et al.*, 2017) to exercise programs. For upper limb stroke rehabilitation, technology needs to be able to track and record a user's hand movement. A precondition of technology for upper limb stroke rehabilitation is that the technology should record the person’s limb positions/orientations to allow interaction with the Virtual Environments (VE) and measure performance.

This chapter expands on Burkes (Burke, 2011) review of the rehabilitation technologies, reviewing the existing and more recent advancements in hardware technologies for interfacing and viewing VEs. A review is provided of current adaptive rehabilitation games and VR technologies, and the potential benefits and problems that they may have for stroke rehabilitation.

# 2.1 ASSISTIVE TECHNOLOGIES FOR UPPER LIMB STROKE

In this section, contains a review and summary of human tracking and interactive technologies currently used for physical rehabilitation of stroke patients.

## 2.1.1 MOTION TRACKING AND INTERFACING TECHNOLOGY

### 2.1.1.1 OPTICAL TRACKING DEVICES

Optical tracking is the process of determining changes in motion over-time using one or more cameras, with no tethering required the person has a full range of movement. Motion capture can be achieved using various techniques. Using markers passively, reflective markers are placed on a person's body, and light is emitted from a camera and reflected back from the markers. Active markers are different in that LEDs attached to the person's body illuminate in sequence while the camera tracks the LEDs to determine the position and orientation. Markerless tracking uses computer algorithms to continuously search and compare images to extract the person's body, normally using depth-sensing cameras often seen in low-end motion tracking systems. All optical motion capture techniques can suffer from occlusion due to environmental changes blocking the camera field of view. The design and calibration requirements of some optical tracking devices can mean that a certain amount of space is needed for optimal tracking to occur. One possible solution to the occlusion is using Wi-Fi Signal in a mesh network to track movement through obstacles including walls and around large spaces (Tan *et al.*, 2016;

Booranawong, Jindapetch and Saito, 2018). Notable applications for optical motion capture include facial recognition, animation, mixed reality and augmented reality and computer games. Markerless techniques would be considered less accurate compared to the other techniques but they still produce a high degree of accuracy, and low motion captures latency that is comparable to real time. Some of the low-end commercial devices are now capable of target specific areas of a person's anatomy with high precision. The Microsoft Kinect (*Microsoft, USA,2010*), an infrared depth-sensing camera that can capture motions of multiple human skeletons simultaneously and track facial points for facial recognition and expression detection. The most recent innovation, the Leap Motion Controller (*Leap Motion, USA, 2012*) can detect all the major joints and bones in the human hand through an extremely compact and light infrared depth-sensing camera.

Optical motion capture has been a common sensory approach for physical therapy stroke rehabilitation (Llorens *et al.*, 2015). One of the earlier uses of optical motion capture systems was GestureTek ‘s mandala gesture xtreme (GX) system. GX was made using a chroma-key based setup which overlaid the 2D VEs on the top of the patient's video capture to control the VEs environment. With the Chroma-key setup, GX required considerable setup and space. It was apparent that the use of the GX was beneficial in rehabilitation (Rand, Kizony and Weiss, 2008), but a clear limitation of the system was that it could not be customised to suit different patients’ motor and cognitive impairments. GX was adapted to customise levels of difficulty and record performance outcomes; the adapted system is known as IREX (Weiss *et al.*, 2009). The most robust alternative to the GX and IREX was Sony's Eye Toy (Rand, Kizony and Weiss, 2004) designed for the wider gaming market. The Eye Toy offered a low-cost approach which did not require the use of a chroma-key setup with potential for use in the patient's home. Rand compared the Eye Toy and IREX to measure the usability of each system; the Eye Toy record high usability amongst the participants. However, similar to the GX system the technology and systems where not customisable to include a broader range of motor and cognitive impairment.

The evolution of video capture technology has improved greatly, technology like the Kinect and the Leap motion have provided new and improved video motion capture for better natural interaction with VEs. Microsoft’s Kinect is an inexpensive markerless optical motion tracking device, with the capability to track the motions of multiple human skeletons simultaneously. The Microsoft Kinect can also detect and track a considerable amount of points on a human face for application such as facial recognition and expression detection. The latest version of the Kinect, Kinect V2, has been improved for better hand and face detection. Since the release of the Kinect in 2010, it has been increasingly used in Stroke rehabilitation research (Webster and Celik, 2014). However, recently in 2017 Microsoft stated that the Kinect would be discontinued. A possible reason for the discontinuing of the Kinect is the increasingly effective standard webcam devices that use deep learning techniques to detect body movement (Voinea *et al.*, 2016; Medium, 2017). The Leap Motion Controller is a newer optical motion tracking device that makes use of small infrared depth-sensing cameras to capture all the major bones and joints in the person's hands and arm, comprised in a very small and light casing. The Leap Motion Controller has the potential to be a useful device for upper limb stroke rehabilitation. However, research into the usability and performance of the Leap Motion Controller to date is limited, though initial research demonstrates its potential for VR stroke rehabilitation technologies (Bachmann, Weichert and Rinkenauer, 2014; Tung *et al.*, 2015; D. Holmes *et al.*, 2016; Lupu, Botezatu and Ignat, 2016).

#### 2.1.1.2 SENSOR BASED TRACKING SYSTEMS

Motion capture with sensors allows the tracking of users in 3D space with six degrees of freedom that captures the user's position and orientations. The sensors are attached to the user's joints, recording motion with very high precision of accuracy than other technologies such as optical motion capture. As the sensors are attached to the user's limbs, it provides an effective means of presenting the user's real-world movement information into VEs to enable interaction. Typically, sensor-based motion capture systems require a certain amount of setup and in some cases depending on the limbs being tracked, and the complexity of the movements expected from the user, space to move may be needed. There are several types of sensors that can be used for motion capture, for example, magnetic motion tracking which transmits a magnetic field from a static base station while the user wears 3D electromagnetic sensors. The base station measures the intensity of the magnetic field emitted back from the electromagnetic sensors on the user's body to determine positioning and orientation. These sensors can suffer from interference from other electromagnetics of metal materials; tracking space is also limited by the range of the magnetic field and latency due to the asynchronous nature that the sensor measurements are calculated. Inertial motion tracking - these sensors consist of accelerometers that measure changes linear acceleration over time to determine the person's joint position and gyroscopes to measure the angular velocity, to determine the orientation of the joint. Magnetometers are sometimes used in inertial sensors, to calculate the heading of the joint. A major problem using inertial sensors is that over time accumulated acceleration errors are introduced known as drift causing the positioning of limbs to be disjointed. Mechanical motion tracking sensors are a series of linkages attached to the person's limbs, often described as an exoskeleton, to measure sequences of movement. Usually, mechanical motion tracking systems are built with electrogoniometers – consisting of potentiometers or transducers to estimate joint angles when positioned near or on the person's joint. The accuracy of mechanical sensors is considered less accurate than other sensor-based systems. Below discusses several notable devices that use the different types of sensor-based motion tracking.

Several commercial sensor-based systems have been investigated for use in stroke rehabilitation. Zhou (Huiyu Zhou and Huosheng Hu, 2005) used the MT9 (*Xsens, Netherlands*) inertial sensor to develop a feasible and reliable system to aid stroke rehabilitation of the upper limbs. Zhou concluded the sensors provided a desirable degree of accuracy to develop upper limb kinematics models. However, the research did find drift and noise from the sensors (Huiyu Zhou and Huosheng Hu, 2005), but Zhou later improved on this by using filtering and optimisation methods to reduce drift and noise (Zhou and Hu, 2007; Zhou *et al.*, 2008). Piron used the electromagnetic 3D motion tracking system (*Polhemus 3Space FasTrak, Colchester, VT*), to compared motor learning techniques in a VE against conventional upper limb therapy for post-stroke patients (Piron *et al.*, 2010). Both approaches improved arm motor performance. The Philips Research Stroke Rehabilitation Exerciser, a wireless inertial sensor for measuring user joint kinematics was investigated by Annick to assess patient motivation and system usability; the system was highly rated for usability (Timmermans *et al.*, 2010). The use of mechanical tracking devices is limited in stroke rehabilitation. However, a recent and potential device for stroke rehabilitation is the Dexmo, which is a hand exoskeleton used to track hand and finger movements along with providing force feedback to the user (Gu *et al.*, 2016).

In 2006 the Nintendo Wii was released and since been used for research in upper limb stroke rehabilitation shows that the Wii is improving upper limb function and can be used adjacent with conventional therapy (Saposnik *et al.*, 2010; Mouawad *et al.*, 2011; McNulty *et al.*, 2015). The Wii makes use of two handheld controllers that tracks the motion of the user's hand with inertial sensors. Since 2017 some novel research and technology are being developed with inertial sensors for motion tracking in daily life embedded into clothes. Klassen (Klaassen *et al.*, 2017) developed clothing sensors called INTERACTION, which have the potential for a stroke patient to wear during their daily lives that monitors movement and muscle activity mainly. The clothes include a total of 41 sensors including 14 IMU sensors to track the movement of the person full body. Currently, this technology has yet to be extensively researched using stroke patients but has been reviewed by health care professionals evaluating the usability of the technology. Healthcare professionals favoured and understood the measurement matrices of the sensors. However, there were concerns that set up time, processing, report generation time and the context of data recording at home. Although sensor-based tracking systems have higher precision than other motion tracking methods, they do have drawbacks such as the long time to set up the sensor-based tracking system, the cost can be very high, and these types of systems tend to suffer drift or interference affecting user experience.

#### 2.1.1.3 REHABILITATION ROBOTIC DEVICES

These devices are designed to assist sensorimotor functions (e.g. arm, hand, leg, ankle), therapeutic training and assessment of movement performance of the limbs. Upper limb Rehabilitation Robotic devices can be categorised by assistance active, passive, haptic, coaching. Active devices provide motion assistance, usually includes actuators that can support the movement of the upper limbs. Mainly this type of device is considered for patients when their upper limb movement is too weak. Passive devices are unable to move the patient's upper limbs but make use of actuators as a resistive force against the upper limbs. Patients with movement in their limbs may only be used for passive rehabilitation devices. Haptic robotic devices are considered either active or passive robotics; haptics enables the patient to interface with virtual environments through the sensation of touch. Other robotic devices that don't necessarily provide assistance or resistance to movement; these devices provide different feedback. These devices are labelled coaching devices and serve as input devices, mainly interaction with virtual environments. Coaching devices usually track limb movement and provide feedback about the performance of the user (Maciejasz *et al.*, 2014). Robotic devices can sometimes limit the movement of the patients with some devices using as little as two degrees of freedom. Most robotic rehabilitation exercise programs only focus on one aspect of rehabilitation such as motor rehabilitation and cognitive rehabilitation and not all devices are capable of training fine motor skills. VR adapted robotic devices remain limited in the way they provide natural interaction with the VEs (Li *et al.*, 2014). Rehabilitation robotics can be used to target specific movements or limbs. The Amadeo robot (Hwang, Seong and Son, 2012; Sale, Lombardi and Franceschini, 2012) is a robotic device concerned with the movement of the hand and individual finger movements. The ARMin generations of rehabilitation robotics are noted well in rehabilitation literature (Nef *et al.*, 2009; Ren, Park and Zhang, 2009; Staubli *et al.*, 2009) the most recently published work mentions the ARMin III (Tobias *et al.*, 2010). These devices are exoskeleton robots with the ability to move and track the patient's shoulder, elbow and hand with three degrees of freedom. ARMin III has since been commercialised, now known as ArmeoPower. Other popular and similar robotics devices include NeReBot (Stefano *et al.*, 2014), InMotion (Labratories, 2017).

## 2.1.2 USER EXPERIENCE AND INTERACTION TECHNOLOGY

### 2.1.2.1 EMG DEVICES

Electromyography (EMG) devices consist of one or more sensors that are capable of evaluating and recording the electrical signal produced by the muscles in the human skeleton. EMG devices process this electrical signal information into computer-readable data that allows users to control computer applications such as games, presentation slides, or other multimedia applications. To date, the majority of EMG applications in stroke rehabilitation focus on using biofeedback training to help patients manage their physical and mental condition by receiving performance information of his/her actions during rehabilitation to encourage users to improve on their performances (H. and C., 2007). Some of the more recent EMG devices developed that have potential in the rehabilitation of motor function include the Myomo 1000 (Peters, Page and Persch, 2017), E-Link (Bae *et al.*, 2015) and more recently the Myo Armband (D. Holmes *et al.*, 2016; Hidayat, Arief and Yuniarti, 2017).

### 2.1.2.2 BRAIN-COMPUTER INTERFACES

Brain-Computer Interfaces (BCI) are computer-based devices that read brain signals using sensors called electroencephalograph (EEG), the signal readings are then converted to computer readable information that can be used to command and control computer applications. There are two approaches that BCI devices can be used to aid stroke patients. Firstly, it can be used as a substitute for the loss of motor function by using the stroke patients brain signals to interact with the environment such as controlling the movement of a cursor on the screen. The second approach is to use BCI devices to recover the motor function of stroke patients; it is possible for BCI devices to encourage and guide activity-dependent brain plasticity by using exercises that encourage activation or particular brain signals. Much research has been done on BCI for stroke rehabilitation and seems to show potential for use in stroke rehabilitation (Ang and Guan, 2013). However, there are still challenges to using BCI devices with healthy and upper limb impaired people. Maskeliunas (Maskeliunas *et al.*, 2016) investigated the usability of commercial BCI devices with healthy participants and mentioned some of the challenges that researchers may face using BCI devices; some BCI devices often require a considerable high computational capacity for real-time signal analysis. Commercial BCI devices can be inaccurate and have a low transfer rate. Currently, BCI's ability to read brain signals has high-performance variability between users; this is known as BCI illiteracy. BCI illiteracy is not fully understood, and more research is required. However, it is suggested that it could be a result of individual user characteristics (mental and physical condition). Another issue is noise interference from user muscle movement, eye-lid movement (blinking), pulse artefacts (electrodes placed on a pulsing blood vessel). More research is required to solve these issues before users can have an enjoyable, reliable, comfortable and user-friendly experience. Several recent commercial BCI headsets have been used for stroke rehabilitation research, assessing the performance and feasibility of BCI devices. The Emotiv EPOC (Jure *et al.*, 2016; Verplaetse *et al.*, 2016) seems to show the most promising results in performance. Others include NeuroSky (Jang, Kim and Lee, 2016) and OpenBCI (Vourvopoulos, Ferreira and Badia, 2016).

### 2.1.2.3 INTERACTIVE HEAD MOUNTED DISPLAYS

Interactive head-mounted displays or VR Headsets are devices worn on the head over the user’s eyes to view the VEs. VR headsets are designed to immerse users in a 360 VE and track the head movement to orient the user’s view in VR. There are two main types of positional head tracking. They are outside-in and inside-out, the former is where the headset position is tracked using a fixed external sensing device, and the latter uses a camera attached to the headset sensing the change in the environment in front of the user and their positional change. The hardware of the VR headset consists of a small screen(s) placed inside the headset that is separated into a pair of identical images side by side, one for each eye. On top of each image, lenses are placed to focus and reshape the images for each eye to create a stereoscopic 3D image. Embedded into the headset is an IMU sensor used for tracking user orientation inside the VEs. HMDs have existed and have been used in VR stroke rehabilitation for a while now. (Jaffe *et al.*, 2004; Crosbie *et al.*, 2008; Jannink *et al.*, 2008; Jinhwa, Jaeho and Hyungkyu, 2012; Lee, Kim and Lee, 2014). The continual development in HMDs has provided the potential for greater immersive VR rehabilitation. More recently HMD devices have taken a considerable step for an immersive experience, devices such as the Oculus Rift, HTC Vive, and mobile HMDs for the latest smartphones such as Samsung Gear VR and Google Daydream offer potential improved immersive qualities and better ways to interact with the VE. The Modern VR Headsets include Handheld controllers for interaction and to receive haptic feedback. Also, the sensors in the modern headsets provide functionality to use head position and orientation tracking to interact with menus, buttons, and virtual objects similar to how a mouse is used to control a cursor on screen, it is also possible to monitor head tracking for feedback on body position for posture and movement correctness during rehabilitation. This may be beneficial to reducing the complexity of non-rehabilitation interactions such as button clicks, or scrollbars. This can reduce cognitive and physical learning and effort, helping to minimise fatigue so that more rehabilitation exercise can be performed. Most of the HMDs also provide various styles of handheld controllers for advanced interactions within 3D VEs. An ergonomic handheld controller may provide easier ways of 3D interaction while also being used for simple hand tracking. However, a possible disadvantage to handheld controllers is the difficulty for upper limb impaired users to hold/grasp, move (hindered by weight or friction), and release the controller on demand. Important issues that VR developers/designers should take careful consideration of when creating VEs are motion sickness, vertigo, and headache conditions that may cause user discomfort through poor interaction design. Research has given rise to helpful guidelines for reducing the side effects of wearing HMDs, Table 2-1 shows the common side-effects of wearing an HMD (Sharples *et al.*, 2008; Jason, 2015). Currently, there is limited research directly investigating the usability, acceptability and their effects on motor learning. Research that has directly focused on the performance of the HMD's for stroke rehabilitation mainly found that using an HMD, users’ movements were slower with more variation in movement but suggested that it may be possible to improve movement coordination with prolonged use of the HMD (Subramanian and Levin, 2011; Just *et al.*, 2014).

**Table 2-1: Common side effects of wearing an HMD**

| Side effects of HMDs | Prevention guidelines |
| --- | --- |
| Motion Sickness | Motion sickness is the most common adverse effect of VR. It is a feeling of sickness as a result of motion in VR; symptoms include nausea, dizziness, headaches, vertigo, drowsiness, pallor, sweating, and in worse cases vomiting. There are several theories of how motion sickness occurs and when designing VR all these theories should be considered. |
| Eye Strain | Eye-strain can occur through Accommodation-Vergence Conflict (When objects are too close or too far away from the eyes), Binocular-Occlusion Conflict (occurs when occlusion cues do not match binocular cues) or Flicker (Flashing, repeating of alternating visual intensities). Designers should take careful consideration of the use of depth in VR scenes. |
| Seizures | Photic seizures and can occur in VR where there is flashing, or flickering light and it would be advised that design should avoid overuse of flashing and flickering light. |
| Latency | Latency is the true time taken for a system to respond to a user action, from the start of the movement to the render of the pixel on the screen. For VR it is unclear of the max latency a system can experience before it has negative effects on the user as the system technology varies. It is advised to keep latency as low as possible. |
| Physical Fatigue | Physical Fatigue can be a result of multiple causes such as headset weight, holding unnatural poses, navigation techniques that require physical motion for a period and, standing can also be tiring. A rest from the VR system is good to reduce tiredness, if the VR requires standing, a sitting option should be considered for long sessions. |
| After effects | After using VR, problems may persist when returning to the real-world, after effects include disorientation and flashbacks. People who experience most VR sickness tend to experience the most after effects. It is recommended that if after effects are experienced, the person should rest for one to two hours. |

**Table 2-2: A summary of the advantages and disadvantages of the technology reviewed**

| Technology | Advantages | Disadvantages |
|---|---|---|
| Kinect, Leap Motion Controller, GestureTek | • Low latency<br>• Some devices are compact<br>• Low cost<br>• Low drifting<br>• Untethered movement | • Visual occlusion issues<br>• Some sensors require a significant amount of physical space<br>• Issues with variable light conditions |
| Nintendo Wii, INTERACTION, | • High precision<br>• Does not suffer occlusion | • Can suffer from drift or interference (magnetic)<br>• Requires longer setup time<br>• High cost |
| ArmeoPower, NeReBot, InMotion | • High Precision<br>• Does not suffer occlusion<br>• Supports assistive & resistive movement | • Range of motion can be limited<br>• Limited immersive experience<br>• High cost<br>• Requires fixing to user<br>• Limits the number of therapies that could be used |
| E-Link Myomo 1000, MYO Armband | • Can identify individual muscle activation & deactivation.<br>• Can monitor muscle performance. | • Requires fixing to user<br>• Most remain expensive |
| Emotiv EPOC, NeuroSky, OpenBCI | • Increasingly inexpensive<br>• Can monitor brain activity progression during rehab | • Low transfer rate<br>• BCI illiteracy<br>• Interference<br>• Invasive and can be difficult to wear on the head |
| HTC Vive, Oculus Rift, Google Daydream, Samsung Gear VR | • Highly immersive<br>• Enable head and hand tracking for UI interaction movement performance assessment. | • Requires fixing to the user’s head<br>• May produce temporary health issues (motion sickness).<br>• Inside-out tracking can cause drifting<br>• Outside-in can be affected by occlusion. |

## 2.2 REHABILITATION VR AND GAMES

Conventional repetitive task training for some aspects of upper limb stroke rehabilitation has been successful in maintaining and improving upper limb function (Veerbeek *et al.*, 2014). VR is still a relatively recent intervention in rehabilitation and is defined as a computer-generated interactive simulation of engaging 3D environments that can be interacted with, in a natural and physical way, by a person using interactive and immersive hardware. VR in rehabilitation is becoming increasingly predominant mainly due the advancement, accessibility and affordability of the recently released technologies. However, VR and gaming have not been established as a consistent rehabilitation intervention in rehabilitation clinics and Burridge's (Burridge and Hughes, 2010) systematic review states that is due to the lack of evidence of the effectiveness and usability of the VR technology. To date, more research has been undertaken to investigate VR to improve upper limb function. A recent Cochrane review of 22 studies with 1033 participants (Laver *et al.*, 2017), reviewed VR for upper limb function and found that the addition of VR to usual care resulted in improved upper limb function. However, VR was not a more effective approach than conventional therapy. Patients may benefit more from VR rehabilitation alongside their normal rehabilitation program. Many researchers and clinicians have made use of VR through commercially available games from ubiquitous game consoles such as the Wii, PlayStation and Xbox to deliver VR rehabilitation. These systems are primarily designed for entertainment and recreational purposes but have been adapted by clinicians for rehabilitation purposes. Increasingly it is the case that custom developed VR and gaming systems are being developed specifically for rehabilitation; to address the limitations that commercially available VR and Games have struggled to provide for rehabilitation. Challenges include the ability to accurately adapt the games to match the skill of the individual stroke patient, provide task-specific movements of ADLs, provide specific feedback of knowledge of results and knowledge of performance. The benefits of custom rehabilitation systems are discussed in more detail in section 2.2.2. Searching in the research literature, a number of notable VR rehabilitation systems used in the research were found and are described below in the next section.

## 2.2.1 EXISTING UPPER LIMB VR AND GAME REHABILITATION SYSTEMS

### 2.2.1.1 REHABMASTER™

Joon-Ho Shin, Hokyoung Ryu and Seong Ho Jang (Shin, Ryu and Jang, 2014) developed a task-specific game-based VR rehabilitation system called RehabMaster. RehabMaster uses a vision-based approach to track and monitor user upper limb movements; the technology used is a Primesense 3D infrared depth-sensing camera attached to a PC and 60-inch monitor. The patients sit in front of the Monitor facing the Primesense camera, and the user's movement is used in the games. RehabMaster is controlled by an occupational therapist (OT) on a separate computer connected to the RehabMaster via a local network connection to control the patient’s training and level of difficulty. 20 participants took part in assessing the usability of the RehabMaster over a two-week period (two sessions a week). A questionnaire was used that focused on user experience, i.e. attention maintenance, enjoyability, and motivation. They found that participants were able to maintain their attention very well and have an enjoyable experience without any negative feeling towards RehabMaster. Clinician perception on the use of RehabMaster for stroke rehabilitation was also evaluated. Clinicians were highly acceptant of the control mechanisms for adjusting training, and one OT said that many patients felt satisfied with the adjustable difficulty of the rehabilitation program. However, one PT did mention that there was a lack of finger flexion and extension training.

Two clinical trials were conducted, the first trial recruited six chronic stroke patients to take part in the trial for two weeks using the RehabMaster for 20 minutes, five days a week. Over the two weeks, improvement in the Fugl-Meyers Assessment (FMA) was observed, but it was not a significant improvement. The modified Barthel Index (MBI) increased over the trial indicating a consistent effect over time. The second trial was a randomised control trial and recruited patients with an acute or subacute stroke. Nine patients where give the RehabMaster, and the occupational therapy and seven received occupational therapy only. Results showed an improved FMA score with participants that received the RehabMaster and OT compared to those who received OT only. MBI did not differ significantly between the groups.

The results suggest that the RehabMaster was effective with patients in the chronic stroke phase.

### 2.2.1.2 REHABILITATION GAMING SYSTEM

The Rehabilitation Gaming System (RGS) is a vision based hand and arm tracking system that uses virtual reality and gamification approaches (Cameirão *et al.*, 2007, 2012). The technology is PC based and uses a Microsoft Kinect to track the user's hands and arms in real-time to enable interaction with the VEs and games. The game's difficulty can be adapted for each person in real-time to help optimise visual feedback to users. RGS provides a variety of games and themes. A user interacts with the RGS by placing their hand on a table and moving it along the table. The Kinect detects this motion which is used as controller input for VEs and games (Eodyne, 2018). A randomised control trial was conducted to assess the usability of RGS; nine participants received the RGS for 20 minutes (Cameirão *et al.*, 2010). After using the RGS, each participant was given a usability feedback questionnaire to assess the acceptance of the training and the overall satisfaction of RGS. When asked if RGS was enjoyable, 88.8% of participants enjoyed using RGS (four strongly agreed, four agreed) while one of the participants did not agree or disagree. The statement “the task was easy” seven of the participants agreed (two strongly agreed, five agreed), one participant was undecided, and one disagreed with the statement. It was concluded that the response showed acceptance of the RGS as an upper limb rehabilitation tool among stroke patients.

### 2.2.1.3 ELINOR REHABILITATION GAMING TOOL

Elinor was developed at InGaMe Lab, University of Skovde, Sweden. It is designed to be a complete, custom, home-based rehabilitation system; the system is a PC based game console with the hardware components assembled in a single box. A unique USB memory stick is given to each patient and is used as a key to access the system features and to read individual patient configurations for the games. Once switched on with a few simple actions, interactions with system uses two custom-designed handles (one for each hand) that track the 3D motion of the user’s hands with three degrees of freedom (Taylor *et al.*, 2009). The movement is then translated into the games for interaction. An initial evaluation of the usability of Elinor was conducted (Backlund *et al.*, 2011) with five stroke patients. The general response from the participants was positive, all but one participant was motivated to take part and on average recorded 22 hours of gameplay on 57 separate sessions. There were no major problems with the method of interaction with Elinor and several patients mentioned that they became immersed in the gameplay. The initial study concluded that the Elinor system enhances patient motivation for rehabilitation at home. The evaluation of motor recovery was assessed, they used a number standardised measure before and after a five-week period while using the Elinor system. Results showed that no person suffered any adverse effects while use Elinor. The Action Research Arm Test (ARAT) measure showed improvement in 3 of the 5 participants; the ARAT assessment suggested that one patient seemed to have deteriorated. The Assessment of Motor and Process Skills (AMPS) showed that all participants had improved their ability to perform personal and instrumental ADLs. However, the results of the AMPs assessment was not deemed to be significant. The Motor Activity Log (MAL) self-reporting results showed that most participants felt they had improved. It was concluded that the results of the motor assessment as enough to motivate future work using the Elinor system.

#### 2.2.1.4 MINDMOTION PRO

The MindMotion Pro is a VR based rehabilitation system for the functional training of the upper limbs after brain damage from Swiss company MindMaze. MindMotion PRO consists of a touchscreen monitor with an embedded computer; a 3D motion-sensing camera is attached to the computer for tracking and interpreting the user's hand and arm motions into game scenarios. For tracking of the forearm and wrist for specific exercises, inertial sensors are placed on the specific location of the user's arm and hand, and the movements are mapped to an avatar in the VE. The avatar is seen from a first-person perspective for real-time embodied visual feedback. The results of a pilot study (Perez-Marcos *et al.*, 2017) showed that the usability and acceptance of the technology were positively received after all sessions of MindMotion PRO and it also showed potential for improving upper limb function.

#### 2.2.1.5 OTHER VR REHABILITATION SYSTEMS

*Virtual Reality Rehabilitation System* (VRRS) - by Khymeia (Lencioni *et al.*, 2016), is a comprehensive virtual reality system for rehabilitation and telerehabilitation. Features include, highly customisation capabilities, automatic reporting, telerehabilitation functionalities, and a magnetic kinematic acquisition system used for monitoring rehabilitation. One concern for rehabilitation is that the wearing of multiple sensors may be cumbersome, and patients may need assistance to wear the sensors on the body.

*VirtualRehab* - by Virtualware (Virtualware, 2018), is an innovative physical rehabilitation system based on video game technology utilising Microsoft's Kinect to enable the monitoring and tracking of patient progress from anywhere in the world. Patients can perform complex rehabilitation programs using entertaining therapies either in a stroke rehabilitation centre as well as in their own homes.

*SeaboVR* – by Saebo (Saebo, 2018) is a virtual ADL rehabilitation system designed to engage upper limb impaired users in physical and cognitive rehabilitation. The system makes use of an optical tracking device for tracking of the upper limbs. ADL tasks include shopping, restocking the fridge, and preparing dinner. The system has shown to improve upper limb function (Adams *et al.*, 2018).

### 2.2.2 BENEFITS OF REHABILITATION SYSTEMS

#### 2.2.2.1 PERSONALISED AND ADAPTIVE REHABILITATION PROGRAMS

Due to the flexibility and the different approaches to designing the interactions within the VEs, it is possible to develop goal/rehabilitation specific exercises that can be used to interact with the VE. It is possible for technology-based systems to continually monitor the user's movements to profile their performance in the tasks and adjust the goals of the patient's rehabilitation program as well as the frequency, difficulty, and intensity of the training exercises to provide exercises that are suited to the capabilities of the individual's motor skills. Currently, in conventional therapy a therapist will continually observe the user in person and adjust the difficulty of the exercise according to the stroke patient's performance in the rehabilitation exercises; this can be a time-consuming process for the clinician.

### 2.2.2.2 FEEDBACK

VR supports multi-modal feedback that can be used to provide knowledge of correctness of movement, give users an understanding of their actions and the quality of their actions to aid further motor learning and motivation for continuation with their VR rehabilitation program. Feedback can be given to the user in two main forms. Knowledge of results (KR) - this is concerned with how successful a rehabilitation exercise was performed such as game rewards and cues, knowledge of performance (KP) – is feedback related to the quality of the rehabilitation exercise performed such as trunk range of movement, or hand trajectories. Fluet's review (Fluet and Deutsch, 2013) on the use of both types of feedback found that their usage was highly variable with most research predominately focused on the KR feedback and that there was no clear indication that KP and KR were superior over KR alone. Subramanian (Subramanian *et al.*, 2013) use both KR and KP feedback in a VR shopping experience with upper limb impaired stroke participants. He found that the addition of KP for feedback to the user on trunk displacement performance improved elbow extension without compensatory trunk movement, suggesting KP may be an effective medium for providing feedback.

### 2.2.2.3 HOME BASED REHABILITATION

Advancement in technology and innovative design coupled with the drop in the cost of technology has made it increasingly possible to provide a VR rehabilitation solution that is safe, easy to set up and operate in the comfort of the patient's home. Home-based rehabilitation technology that provides motivational characteristics can encourage increased adherence to the user exercise program to aid a faster improvement in motor recovery. A home-based rehabilitation system can provide the user with independent rehabilitation. Therapists are usually required to visit patients at home regularly. This can be time-consuming and can incur high costs for health services. Home-based rehabilitation has the potential to reduce the time and cost of a therapist and health services.

### 2.2.2.4 DATA LOGGING AND TELEREHABILITATION

Various types of data can be stored about the user's performance, interactions, and usage during their VR rehabilitation sessions at home, which can be beneficial for post analysis by a clinician. The data can also be stored online on a remote server that facilitates telerehabilitation so that the data can be made available to clinicians to be viewed and analysed remotely. Possible benefits to telerehabilitation may contribute to saving travel time and costs for therapists and health services. Telerehabilitation requires a reliable internet connection, and this may be an issue for users with a weak internet connection, other issues include firewalls and antivirus software blocking data transfer.

### 2.2.2.5 SOCIAL AND COMMUNICATION

A stroke patient can feel very isolated due to the extremity of their condition, as they may have limited mobility or have aphasia; this can provide challenges for them to socialise. Social support can be as important as physical therapy and may encourage faster motor function recovery in stroke patients (Caswell, 2015). Chest, Heart and Stroke and the Stroke Association set up regular social support groups all around the UK to allow stroke patients to chat and share experiences with each other. This can help the emotional recovery of stroke patients, and stroke patients can challenge and motivate each other to go beyond their typical rehabilitation program. It is not possible for stroke patients to go out to the support groups due to reasons such as their mobility, aphasia, travel, illness or the support group are not scheduled on certain days. VR and gaming activities are predominantly online today which offers opportunities for users to get together virtually to chat, share experiences, and play games with each other. It is possible that when stroke patients have no access to social support groups that VR's social capabilities can help friends, family and other stroke patients stay in contact with each other. A social platform for stroke patients, EVA Park, was developed by Jane Marshall and others for the treatment of Aphasia (Marshall *et al.*, 2016). Using multi-user online VEs, they allowed stroke patients to take part in daily language sessions with their support in the VEs. Results showed a high level of compliance with the intervention and significant improvement in tests of functional communication of the participants. Using the RGS mentioned in the previous section, Ballester investigated a multiplayer version of the RGS hypothesising that it would have a positive effect on the involvement of stroke patients in their physical therapy. She found that the social and competitive engagement improved patient performance and enjoyment during the physical therapy tasks (Ballester, Badia and Verschure, 2012).

#### 2.2.2.6 OTHER BENEFITS

*The potential for practising unsafe real word scenarios* - Rehabilitation technology interventions provide a safe environment for patients to rehabilitate. Technology can also provide ways of training ADLs that are deemed unsafe in the real world. For example, training how to make a cup of tea/coffee in VR means the patient is in less danger of burning themselves.

*Variation in VEs* - VR can facilitate the simulation of fantasy or realistic environments. Having a realistic environment while practising ADLs may increase the relevance of the training for the users and further motivate them. A fantasy environment may help suspend the user's disbelief and distract the user from thinking that they are currently performing their rehabilitation exercises, providing an enjoyable experience that is motivating the user to keep playing thus adhering more to their rehabilitation exercises.

### 2.2.3 POTENTIAL ISSUES WITH REHABILITATION SYSTEMS

#### 2.2.3.1 DEPLOYMENT AND PORTABILITY

One of the biggest challenges in home-based rehabilitation is minimising the amount of space required to set up the technology. Some technologies can be large or have multiple components that need to set up around the home for tracking such as depth-sensing cameras like the Microsoft Kinect or HTC Vive. Users' homes can vary in size, so it is important to have technology that is compact and uses as little space as possible but also be easy to set up.

### 2.2.3.2 PATIENTS’ AND THERAPISTS PERCEPTIONS

People that have had a stroke may be cautious about trying new rehabilitation approaches especially those stroke patients that have been in a rehabilitation routine for quite some time. IT illiteracy may also play a factor when using new technology for the first time. It may also be possible to change these perceptions of technology by allowing more willing stroke patients to persuade the unwilling participants, proving that the solution works for others may help, and therapist recommendations can have a big impact in participation. However, the clinician can also hesitate to adopt technology rehabilitation solutions if it is not clear of the outcomes for patients, disrupting their therapy routine and techniques. Training both patients and therapists may help encourage adoption of the new technology (Hochstenbach-Waelen and Seelen, 2012).

### 2.2.3.3 HAZARDS AND SIDE EFFECTS

Technology is becoming more user-friendly, but some technologies can still be harder to use than others. Wired technology can restrict movement as well as causing a safety concern for stroke patients as they may trip or tangle themselves causing an injury. Wearable sensors can be troublesome for the stroke patient to place on their body. This may frustrate the users and may result in them refusing to use the technology. HMDs although have improved vastly, they can still cause motion sickness. Motion sickness is the term to describe the side effects of immersive VR, including nausea, vomiting and disorientation. It is not fully understood how to stop motion sickness from happening, but there are techniques to reduce the effects such as narrowing the field of view, using a virtual, fixed nose as a reference in VR (Nasum Virtualis), reducing rotational motion, and giving the user full control of their movement. There are also several theories to how motion sickness occurs, and it is advised that all the theories should be considered to minimise the risk of users experiencing motion sickness popular theories include sensory-motor theory, evolutionary theory and postural instability theory (Jason, 2015). Motion sickness can cause stroke patients to become cautious of HMDs unless the effects are minimised.  Other common side effects of VR include seizures, eye strain, latency, physical fatigue, and after effects are explained in more detail and how to minimise their impact in Table 2-1.

#### 2.2.3.4 CLINICAL EVIDENCE

In the latest Cochrane review (Laver *et al.*, 2017) where 72 RCT studies with 2470 participants compared an upper limb VR intervention against conventional therapy, concluded that virtual reality might not be more effective than conventional therapy. This is not surprising as it is expected that one to one physical rehabilitation would be more effective, but VR may be a helpful addition to speeding up recovery. The quality of the evidence was low, and most studies had a small sample size. The review states that larger studies are required to confirm the initial findings. These results are encouraging and could suggest that with further research virtual reality could be a promising addition alongside conventional therapy. Fluet and Deutsch conducted a systematic review (Fluet and Deutsch, 2013) on the current trends and gaps in knowledge when using VR as a rehabilitation tool, they raised two important questions that are considered important for adoption of VR as a clinical application. Firstly, they stated, what are the minimum cognitive and perceptual requirements to use in VEs for sensorimotor rehabilitation to be effective? Secondly, how will difference in motor severity, chronicity and the type of task affect the interaction with VR system capabilities and dose requirements? Future studies should address these questions to improve the effectiveness of VR as a rehabilitation tool.

## 2.3 INTELLIGENT USER INTERFACES

User interfaces (UI) are defined as interfacing components that allow users to interact and communicate with a computer application using input devices such as the traditional mouse and keyboard. Interfacing components such as buttons, text fields, scroll sliders, tooltips and so on help give users ease of access, understanding and facilitate interaction. A good UI will aim to be consistent and predictable in the layout and interaction methods. Doing this will increase the usability of the UI and thus the computer application. In general, an adaptive user interface (AUI) is a UI that changes its layout and elements to the needs of the user. For a UI to adapt, it requires knowledge about the user or context, such as screen size. This knowledge can be interpreted as the information that is used to adjust the UI layout and elements to suit the user’s devices. An intelligent user interface (IUI) involves an aspect of artificial intelligence (AI) and requires that the application has knowledge about the user to model and understand the user’s needs to facilitate the personalisation and adaptation of the UI, typically changing the layout of the UI elements to suit the user. A common use of AUI’s is in medical devices; the AUI is used to differentiate and specify which information should be shown to the different types of users, e.g. a patient will be shown a limited level of detail than a doctor would.

From a physical rehabilitation perspective, the primary use of AUI and IUIs is to adapt the rehabilitation focused interactions and tasks, for the automation and adjustment of the level of difficulty of the interactions to match each user’s motor skills in real-time. This is particularly important for home-based rehabilitation, a technology that has an arbitrary level of difficulty will only include stroke patients with greater mobility and not account for those users that have less mobility. Another reason to have adaptive interfaces is to account for improvements and deteriorations in mobility as stroke patients’ motor skills will not always remain the same. Several factors can affect the person’s motor skills such as fatigue, mood, time since physical therapy, and concentration levels. It is possible that an adaptive rehabilitation system can consider the user, by modelling aspects of the user's interaction behaviour, movement performance, and mood. The adaptive technology can match the level of difficulty to the user’s motor skills to give a personalised, user-friendly, and enjoyable experience towards encouraging adherence to their rehabilitation program.

## 2.3.1 ADAPTIVE REHABILITATION TECHNIQUES

This section reviews the main techniques found in VR stroke rehabilitation used for the adaptation of the VR difficulty levels.

### 2.3.1.1 ARTIFICIAL NEURAL NETWORKS

Artificial Neural Networks (ANN) are an artificial intelligence technique that are loosely modelled on the processes of the human brain. ANNs consist of artificial neurons inspired by natural neurons in the brain; they receive one or more inputs that can be weighted to increase the strength or impact it has on the result of the activation function in each node. The output of the activation function known as the node value can be fed into other nodes as inputs to further learn an optimal output value(s). When an ANN is structured, it requires training to learn the appropriate optimised weights; this requires a training data set and can take time to complete the training process. Sometimes an ANN never learns possibly due to the lack of specific information from which the desired output is derived. ANNs can also fail to converge if there is not enough data to complete the learning. Once an ANN is structured and trained, it can begin to output the optimal difficulty level of the rehabilitation tasks, the ANN would take weighted inputs related to the user's performance of the rehabilitation tasks, and the activation functions would output a level of difficulty for the next rehabilitation task(s). The use of ANNs in physical rehabilitation has shown promise in adapting the difficulty in VR and game rehabilitation tasks. One study reported that they found participants' improved motor function when comparing clinical assessments in a pre and post-experiment (Huang *et al.*, 2018). However, in most cases research has focused on the evaluation of ANNs for adaptive rehabilitation technology with healthy participants, and more research should be conducted with impaired users (Barzilay and Wolf, 2013; Shirzad and Van Der Loos, 2013; Dowling *et al.*, 2014).

### 2.3.1.2 FUZZY LOGIC

Fuzzy Logic (FL) is a method of reasoning that resembles human reasoning. The approach mimics the way humans make decisions. Human decision making does not always result in a definite decision; there can be a range of response between YES and NO for example. FL is a computational approach to reasoning, rather than the usual Boolean logic values "true or false" (1 or 0). FL determines values between 0 and 1 to help determine the degree of truth in response. A real-world application of FL in operation is a vehicle's automatic transmission; it takes into consideration factors such as speed, acceleration, and throttle rate of change to determine a value that decides the degree of truth to move up, down or stay in the same gear. For adaptive rehabilitation tasks, fuzzy logic (Karime *et al.*, 2014) has been used for wrist training with healthy participants and users with wrist weakness due to injury. They used three inputs (task angle, average angular velocity and jerkiness) as a measure of wrist movement performance and the fuzzy rehabilitation system outputted a new task angle as a difficulty level of the wrist rehabilitation tasks. It was found that FL did provide a suitable approach to difficulty adaption for wrist training, it was capable of identifying various levels of user performance and did show that it could improve in kinematic performance in impaired users (Karime *et al.*, 2014, 2015). (Zhang, Miao and Yu, 2017) used FL for difficulty adaptation in five elder participants and found that fuzzy logic was effective in predicting the appropriate exercise difficulty for older adults.

#### 2.3.1.3 FITTS LAW

Fitts Laws (Fitts, 1954) is a scientific law that has been commonly used in Human-computer Interaction (HCI) and ergonomics and explains the speed-accuracy trade-off characteristics of the human movement. Fitts Law states that the amount of time it takes to reach a target is dependent on how far away the target is and the size of the target, giving a quantifiable way to measure the difficulty of reaching and touching tasks. Fitts's original equation (2-1) models a user's motor skills by predicting the time to reach and touch a target based on a target's size (W) and the distance (D) from an origin. The logarithmic element of the equation, known as the "Index of Difficulty" (ID), is used to quantify the difficulty for reaching a target. Thus, the movement time (MT) required to touch a target is linearly dependent on ID, where targets that are further away and smaller take more time to hit and targets closer and larger targets take less time to hit. The coefficients $a$ and $b$ are arbitrary constants that are determined by linear regression.

$$MT = a + blog_2\left(2\frac{D}{W}\right) \qquad (2\text{-}1)$$

Other researchers have purposed variations of Fitts's original equation to improve the model in different situations. Two of the popular cited adaptions of Fitts law is Shannon/MacKenzie (MacKenzie, 1989) (2-2) and Welford (Welford, 1970)(2-3) which were originally used to evaluate human movement behaviour for 1D and 2D tasks, they have occasionally been applied in a 3D context. More recent forms of the equation have been devised to represent 3D movement behaviours more accurately. Murata's (Murata and Iwase, 2001) (2-4) proposed an equation for modelling 3D movement, it adapts Shannon/MacKenzie to include the addition of a movement direction parameter into the ID of the Shannon/MacKenzie equation, to account for the consideration that MT is also dependent on the user's angle of motion (θ) from an origin to a target. In this thesis, Murata's equation has been adapted by separating the ID and the movement direction parameters into independent variables for multiple regression. Multiple regression may improve the relationship between the dependent variable and several independent variables (2-5).

$$MT = a + blog_2\left(\frac{D}{W} + 1\right) \tag{2-2}$$

$$MT = a + blog_2\left(\frac{D}{W} + 0.5\right) \tag{2-3}$$

$$MT = a + b\left(log_2\left(\frac{D}{W} + 1\right) + c\sin\theta\right) \tag{2-4}$$

$$MT = a + blog_2\left(\frac{D}{W} + 1\right) + c\sin\theta \tag{2-5}$$

Research recruiting people with upper limb impairment after a stroke reported that Fitts Law was a valid approach for predicting and adapting the level of difficulty for reaching tasks. However, as expected, participant movements in the paretic arm had lower information rates suggesting users were moving slower. Results also showed increased kinematic segmentation and high variation in kinematic trajectory (Zimmerli *et al.*, 2012; Van Dokkum *et al.*, 2015). Kim (Kim, Wininger and Craelius, 2010) conducted a study to investigate the applicability of Fitts Law for grasping exercises with chronic stroke patients using a grip force dynamometer. Fitts Law was capable of quantifying the participants' grip performance and showed that over 12 sessions, users had improved their grasping control indicated by shallower regression line gradients and high correlations ($R^2$). Another study adapted the conventional nine-hole peg test using Fitts Law to predict the movement times for 12 healthy participants when moving a peg from one location to another in 3D. 12 healthy users were recruited and found that Fitts Law and linear regression was a reliable method of predicting movement time but did suggest that a 3D extension of Fitts Law would be more appropriate and may produce improved results (Amirabdollahian, Gomes and Johnson, 2005).

### 2.3.1.4 OTHER TECHNIQUES

*Quadratic Functions* - is an equation of degree two, meaning that the highest exponent of a quadratic function is two. The standard form of a quadratic function is seen in equation 2-6 where $a$, $b$ and $c$ are real numbers, $a$ cannot be zero. A quadratic function always results in parabola graph shape (curved shape). Using a quadratic function, it is possible to model and determine a $y$ value for a given $x$ value. It is possible to use this in determining the level of difficulty of rehabilitation tasks. Cameirão (Cameirão *et al.*, 2010) used a quadratic function to adapt the difficulty of the virtual reaching rehabilitation tasks. The results of the adaptive model showed that the model was able to identify the performance of individual movements of the arms such as speed, interval, range and size, and was able to adapt the parameters accordingly.

$$y = ax^2 + bx + c \tag{2-6}$$

*Thresholding* – Metzger (Metzger *et al.*, 2014) used a thresholding approach with six upper limb impaired users following a stroke. Initially, before performing the robotic therapy sessions a custom pre-assessment was performed, to assess the participant's initial ability to perform certain tasks and used to calculate an initial level of difficulty. From session to session the robotic therapy updated the level of difficulty by calculating a percentage that represents the participant's performance. A performance percentage greater than 70% increased the difficulty, less than 20% it decreased the difficulty, and a result between 20% and 70% resulted in the level of difficulty being unchanged. Exercise adaptation resulted in an average initial performance of around 70%, over the course of the sessions and this was maintained. The progress in difficulty levels correlated with improvements in a clinical impairment assessment (Fugl-Meyer assessment), suggesting that the robotic therapy was effective at reducing sensorimotor impairment.

# 2.4 CONCLUSION

The use and quality of technology useful for rehabilitation continues to grow as the technologies become more advanced providing more responsive interactions, higher accuracy, more cost-effective, and an increasing user-friendly experience. A review of the technology currently used and new potential technology useful for stroke rehabilitation has been presented. The current VR and gaming stroke rehabilitation solutions available to patients have been reviewed along with dynamic difficulty adaption techniques used to give stroke patients easier access to rehabilitation in clinics and more importantly at home. With the recent developments in new technology, it may be too early to say that these technologies are beneficial to stroke rehabilitation as the evidence is still limited. Games and VR prove to be enjoyable experiences and promote adherence to rehabilitation if they are designed well and have shown to improve upper limb function when used adjacent to conventional therapy. Dynamic difficulty adjustment remains a challenge, and current research with impaired users is limited in some adaptive techniques, so it remains unclear if there is a suitable adaptive approach.

# 3 Experimental Design and Rehabilitation System Development

## 3.1 Chapter Overview

This chapter outlines the research method chosen to investigate the application of VR as an assistive rehabilitation technology for upper limb impaired users following a stroke. The importance of users and stakeholders in involvement throughout the development process and the proposal of a novel approach to developing and designing games and gamified rehabilitation solution through the Rehabilitation Gaming Model (RGM) are all described.

## 3.2 Introduction

It is commonly agreed that one of the main reasons for failure to accept new medical technologies is the lack of user involvement in the development process and the time spent on evaluating the usability of the technology with end users (Perry et al., 2009). Designing and developing gamified rehabilitation technologies for stroke patients, requires considerable thought and user involvement, to produce technology that is acceptable to all stakeholders. Stroke patients can benefit significantly from such technology as it can provide a fun way to interact with rehabilitation in clinics or at home, helping them improve their mobility and improve independence in their daily lives. For physiotherapists and occupational therapists, the main benefits are the possibility to monitor the person's adherence to their rehabilitation exercises at home and review progress, if the system is a success in giving more independence to stroke patients then it can allow physiotherapists and occupational therapists to focus their attention on those stroke patients in more need. Automated and self-managed technologies can help carers, and family members become less relied on by the stroke patient to perform activities of daily living reliving stress and pressure potentially experienced by members of the family. Due to the importance of the stakeholder involvement throughout the development process, it would be wise to use a User-Centered Design (UCD) approach to the development life-cycle that predominately involves the end-user to design a rehabilitation system. The UCD process is a common approach to software development (Norman and Draper, 1986) and describes the process throughout the design and development that focuses on gaining in-depth knowledge about the users who will be using the application to develop requirements for design. UCD is based upon obtaining a fundamental understanding of typical users, their actions, and environments; it is driven and refined by a user-centred evaluation addressing the complete user experience (Figure 3-1). Teams in the UCD process most often involve multidisciplinary skills and perspectives to deliver a user-focused product. It is worth noting that the process does not specify an exact method on how to complete each phase.

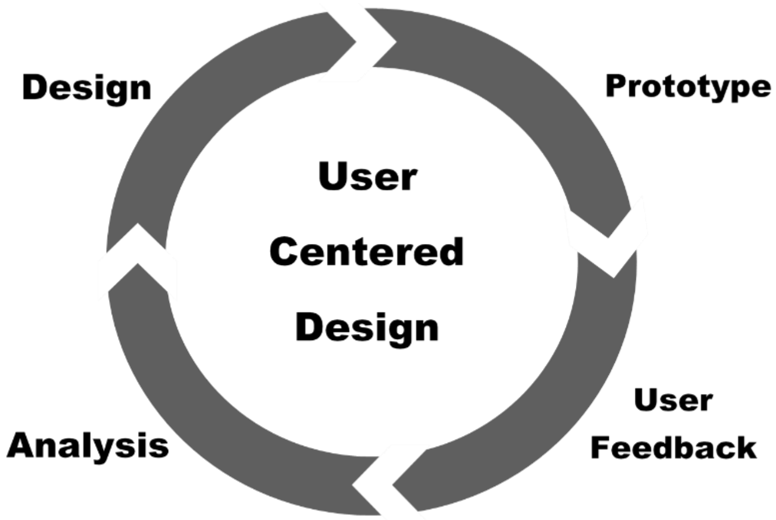



**Figure 3-1: The general phases of the User-Centred Design approach**

## 3.3 SOFTWARE DEVELOPMENT LIFE-CYCLE

In the software industry, there are various development life-cycles adopted to deliver a software solution to market. The waterfall development life-cycle separates the development of a software application in phases traditionally including phases such as requirements, design, implementation, testing, deployment and maintenance. The process is designed with a linear flow meaning that before the development can move to the next phase, the previous phase must be complete with no overlapping phases. Games development companies tend not to adopt the waterfall process due to its linear structure that isn't practical in creating a fun gaming experience as fun is an experimental process require continuous play-testing and prototyping to find a fun experience for the user. The Agile life-cycle has been increasingly used in software development and is focused on dividing the entire software application into smaller, easily developed and shippable products ready for use by the customer. The development is facilitated through incremental cycles known as a sprint that is typically between 1-week and a 1-month timeframe to have a shippable product released to the customer. Agile is being used in game development were the sprints of a game are not exactly shippable games but the working game features delivered within the teams for playtesting (Keith, 2010). Evolutionary prototyping is another development life-cycle in which the development of a software application is created in increments much like Agile, but the prototype after each increment is not a shippable product but is modifiable in response to end-user feedback after users have evaluated it through the use of the application. Increments and changes to the prototype continue until the end-user or customer agrees that the prototype is ready for market. Evolutionary prototyping is a form of the UCD and seems the most suitable development process to produce gamified rehabilitation systems due to its focus on user evaluation for continuous modification and development of prototypes and its flexibility to change features of the systems quickly. User feedback is commonly obtained through both qualitative and quantitative methods, e.g. focus groups, semi-structured interviews, questionnaires, and task analysis. Several usability and UCD studies have been published for rehabilitation games (Lange, Flynn and Rizzo, 2009; Brox, Konstantinidis and Evertsen, 2011; Proffitt and Lange, 2013) and VR as a rehabilitation tool for those with motor impairment (Shin *et al.*, 2014; Proffitt and Lange, 2015)

# 3.4 A PARTICIPATORY DESIGN FRAMEWORK FOR REHABILITATION GAMES

Charles and McDonough (Charles and Mcdonough, 2014) designed a participatory framework made up of four dimensions **P**eople, **A**esthetics, **C**ontext, and **T**echnology (PACT) (Figure 3-2) for the gamification of rehabilitation systems that emphasises the importance of the involvement of the stakeholders from the beginning and throughout of the design. Charles and McDonough describe in Figure 3-3 the typical design flow they undertook in the development of an upper limb stroke rehabilitation application using the Leap Motion Controller device. The PACT Framework can be split into three design phases illustrated in Figure 3-3 and described below:

1. **Phase 1** – is the requirements gathering phase involving a discussion between clinicians, researchers, users/patients and other stakeholders to establish system design criteria suitable for the users' needs and rehabilitation objectives.
2. **Phase 2** – is the main design phase and uses game design and gamification techniques to design toward a more engaging rehabilitation system. The techniques to gamify the systems use models of player motivation and behaviour change. The outcome of phase 2 is a system design developed in conjunction with the stakeholders.
3. **Phase 3** - is the evolutionary prototyping phase where gamified rehabilitation systems are created and integrated with the hardware. The design is evaluated through game evaluation assessment tools by research and development teams. User/Patient, Clinician, Carer/Community feedback is obtained through play and usability testing. Redesign of the system is based on user feedback with the outcome of the stage being a completed rehabilitation system specifically for rehabilitation.

The PACT framework's embedded gamification design approach seems most appropriate for the user-centred approach to developing a gamified rehabilitation system, and it was decided to use the PACT process to structure the development and design of the rehabilitation systems for this research.

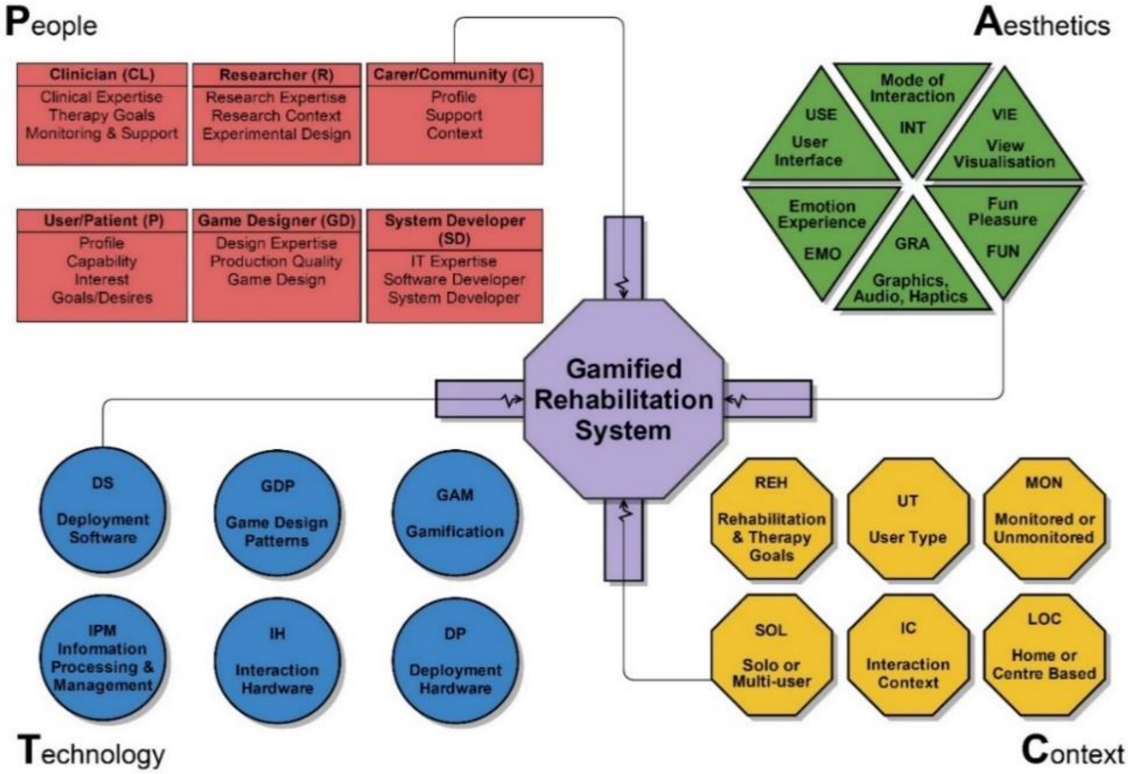



**Figure 3-2: PACT dimensions that make up the participatory design framework**

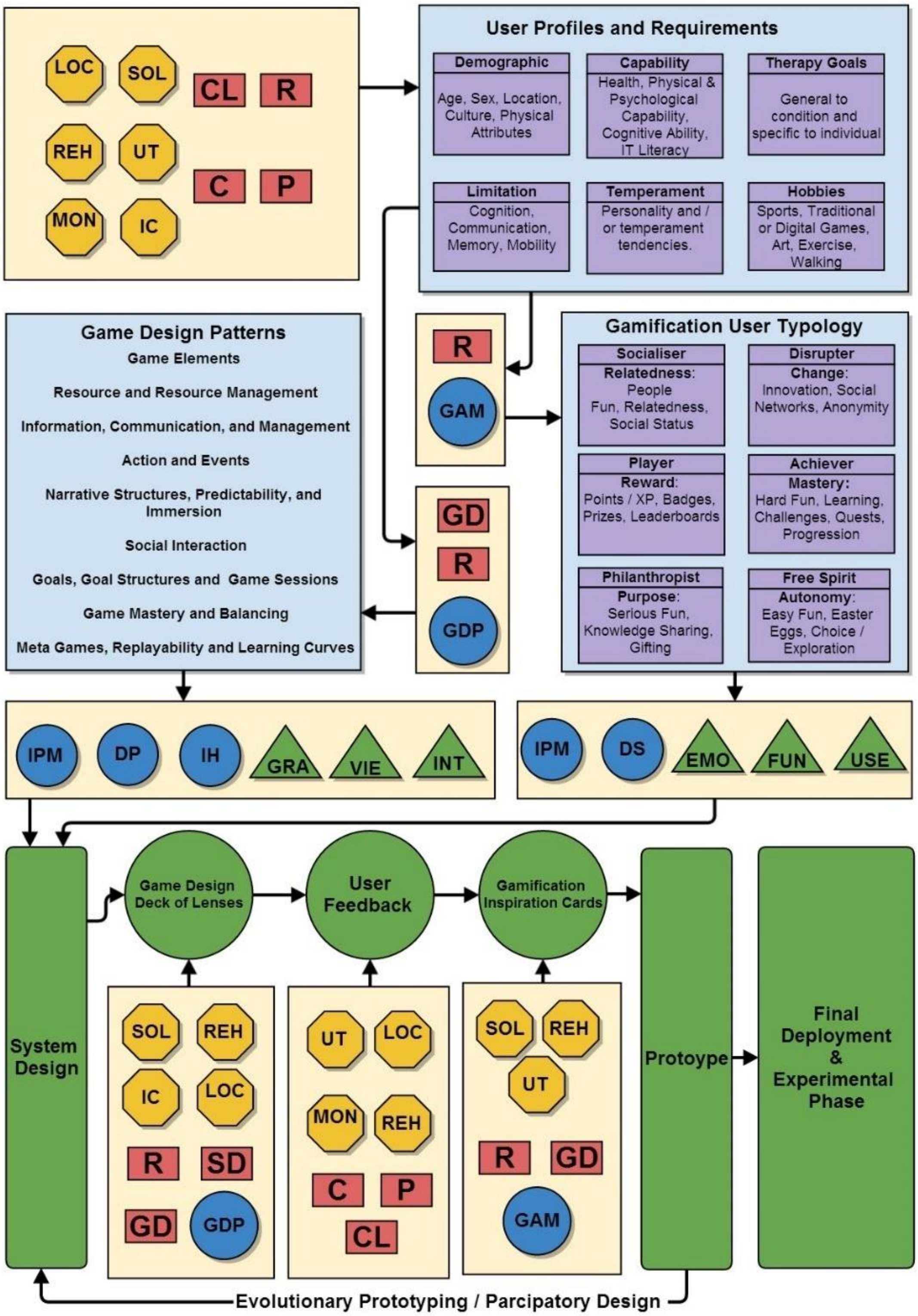



**Figure 3-3: A typical design workflow for the gamification of a rehabilitation system using PACT (see Figure 3-2 for symbol meaning)**

# 3.5 USER INVOLVEMENT & REQUIREMENT GATHERING

This section describes the methods used by the interdisciplinary team, including collaboration, user involvement and demonstration visits to clinics and hospitals, for the development of an adaptive and gamified rehabilitation system. Figure 3-4 shows an outline of the processes and events undertaken for the initial and evolutionary design and development of the rehabilitation system. Descriptions of the Prototype 1 (TAGER) and Prototype 2 (RESTEM) of the rehabilitation system are presented in Chapter 4 and 7, respectively.

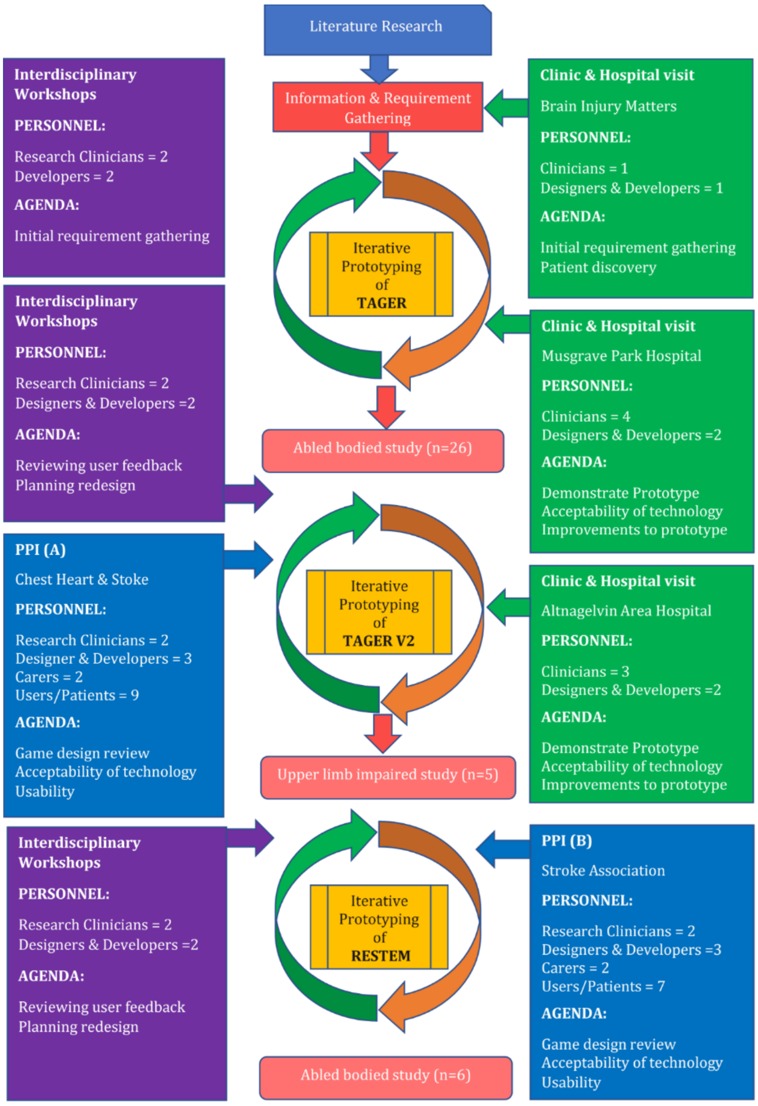



**Figure 3-4: Information gathering methods for the iterative prototyping of the stroke rehabilitation system**

### 3.5.1 INITIAL REQUIREMENT GATHERING

In the initial stages of the research, information was gathered from the existing literature on adaptive and personalised gamified rehabilitation systems for stroke. Visits to the Brain Injury Matters clinic in Belfast to speak to physiotherapists and potential users of the rehabilitation technology was scheduled. The visit gathered information on what physiotherapists and users expect from a rehabilitation system for upper limb therapy and how they would use it. This research and requirement gathering builds on previous research to develop an understanding of the end users, conducted in the research group. The information gathered allowed the identification of initial requirements from the initial interdisciplinary workshop to be communicated to the team (APPENDIX Q).

### 3.5.2 INTERDISCIPLINARY WORKSHOPS

The development of a successful rehabilitation system usually involves a team of people with different skills and disciplines, sharing knowledge between team members to provide clear communication of the design of the rehabilitation system. This helps in speeding up the development process and provides a product more suitable for the specific end users. The interdisciplinary team includes research clinicians, game designers, system developers, and physiotherapists. During the design and development process several interdisciplinary workshops were scheduled initially and between developments of the prototypes. The workshops usually consisted of a full demonstration of the latest version of the rehabilitation system. After which, feedback is given based on different team member perspectives. For example, physiotherapists in the team would evaluate the motor function involved in the system; for its appropriateness and effectiveness for users/patients. Communication of new ideas to improve design were discussed as well as discussions about new requirements and revisit existing requirements to determine if they have been met. User’s feedback from the public involvement (PPI) sessions and the studies conducted is also reviewed, and design considerations are taken into account for the next evolution of the prototype.

### 3.5.3 PATIENT, CARER AND PUBLIC INVOLVEMENT

It is considered good practice to involve patients, carers and the public in healthcare research to lead towards more effective and relevant research. A number of patients, carers, and PPI sessions were planned and implemented throughout the research in conjunction with various stroke organisations that facilitated access to stroke patients and their carers. Two PPI sessions were organised during the research process. PPI (A) was provided at the Chest Heart and Stroke charity in Belfast, where the first prototype was demonstrated to nine user/patients and two of their carers. Users/Patients were also invited to use the rehabilitation system and commercial games (Figure 3-5). Commercial games were included to give patients an experience of a fully commercial game using the VR headset and to get a view on potential gameplay that might engage the patients. This PPI session provided vital feedback from the patients through verbal feedback and observation of their interactions. Questionnaires and focus groups were used informally to collect information about user perceptions of the use of this technology for rehabilitation. A similar approach was adopted in PPI (B) at the Stroke Association in Enniskillen (Figure 3-6) with seven patients and two of their carers, where an improved system prototype was demonstrated. PPI sessions proved a valuable learning experience for all members of the team including myself; learning about the patients' cognitive and physical capabilities and how to interact with patients is important for successful participation by stroke patients in the research studies.

**Figure 3-5: Stroke patients in action using the prototype rehabilitation systems and commercial games**


**Figure 3-6: The stroke patients that participated in the PPI session at the Stroke Association in Enniskillen**

## 3.5.4 CLINIC & HOSPITAL VISITS

Several clinics and hospitals were visited to meet healthcare professionals who support rehabilitation for stroke patients on a daily basis. During these visits, the focus was on clinician feedback rather than the patients; their input helped define requirements to provide a rehabilitation solution that is safe, easy to use and accessible for stroke patients that follows rehabilitation guidelines. Three clinics and hospitals were visited, Brain Injury Matters, Musgrave Park Hospital, and Altnagelvin Area Hospital. During these visits, the current system was demonstrated, outlining the intention of the design and received feedback from patients for future improvements.

# 3.6 GAME DESIGN AND GAMIFICATION

Many design techniques aim to provide fun gaming experiences to motivate and entertain users. Discussed below are several ways to design games and gamified applications and how they may be used for rehabilitation to promote a behaviour change in stroke patients to adhere to their rehabilitation program. This leads towards the design of a tool for designing gamified rehabilitation exercises that encourage a behaviour change.

## 3.6.1 GAMIFICATION

Games are considered to be highly engaging forms of entertainment and the main reason why rehabilitation frameworks have been developed incorporating games to improve engagement with rehabilitation (Charles and Mcdonough, 2014), others have mapped game design components to motor function essential to stroke rehabilitation therapy (Holmes, 2014). Gamification explains the approach of using game elements in non-game contexts such as training and educational applications to provide more engaging and fun experiences to improve productivity and adherence to services (Deterding and Dixon, 2011; Francisco *et al.,* 2012). Gamification aims to make existing and monotonous experiences more enjoyable by applying motivational techniques from games. Some Game mechanics and feedback mechanisms used for gamified applications include rewards, competition and social status elements (Small Business Trends, 2017). A good example of gamification in operation in a health context is Fitbit with the fitness wristbands and mobile app a person can track their fitness receiving achievements for meeting personal goals and compete with friends to encourage users to adhere to their exercises. In rehabilitation, GestureTek (GestureTek, 2017) provides the IREX system with an upper and lower limb impaired rehabilitation system using game elements to provide a fun rehabilitation experience. One common gamification feature used in IREX is the use of achievements for completion of rehabilitation exercises.

## 3.6.2 GAME DESIGN PATTERNS

It is possible for games to be separated into smaller components or mechanics with some game designers attempting to develop different tools for designing games (Bjork and Holopainen, 2004; Cook, 2007; Perry, 2009; Koster, 2012; Deterding, 2013; Nacke, 2014; Schell, 2014). One method that was used in the research consists of a comprehensive game design ontology known as patterns in game design by Bjork (Bjork and Holopainen, 2004). Bjork's pattern in game design gives game designers a means of understanding and choices for creating novel gameplay by selecting a series of game design patterns from categorised lists. The results are a list of selected game design patterns that encourage the user to make choices and think how these patterns may be used in a game. For example, the "*Aim & Shoot*" game design pattern suggests that interaction by the user requires eye-hand coordination to aim at and shoot a target, possibly shooting "*enemies*" (another game design pattern) that are trying to kill you. Goude, (Goude, Bjork and Rydmark, 2007), proposed the use of Bjork's taxonomy of game design patterns for structuring the design of games for post-stroke rehabilitation. Figure 3-7 shows a subset of Bjork's game design patterns mapped to aspects of rehabilitation for stroke patients.

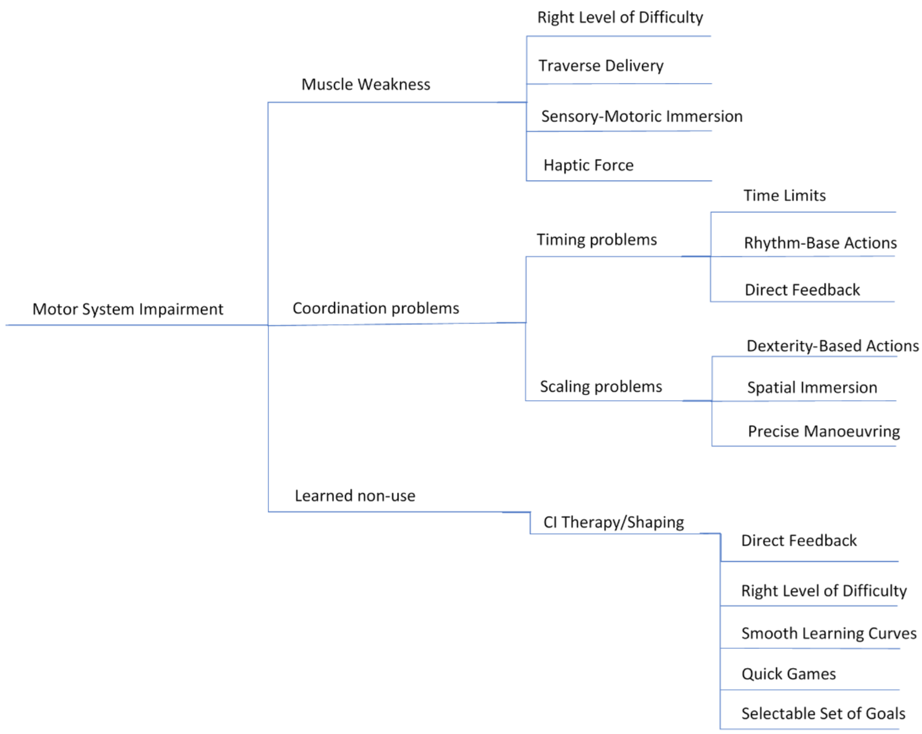



**Figure 3-7: Bjork's patterns in game design taxonomy mapped to rehabilitation components for stroke patients**

## 3.6.3 PLAYER TYPES

Many researchers and game designers have identified variations in the way players interact and the different aspects of games and gamified systems that they are motivated by (Keirsey, 1998; Yee, 2002; Bartle, 2003; Bateman, Lowenhaupt and Nacke, 2011; Marczewski, 2013). Bartle (Bartle, 2003) is the most notable play typology derived from games; he proposed four player types through analysis of player behaviours and interaction within Multi-User Dungeons (MUDs). Bartle's research forms the basis much of the related research including Marczewski's (Marczewski, 2013) Hexad gamification topology, the Hexad is also based on RAMP (**R**elatedness, **A**utonomy, **M**astery, and **P**urpose) from self-determination theory (Ryan and Deci, 2000). RAMP identifies four factors that intrinsically motivate a person. The Hexad consists of six core types of people along with the types of behaviour that motivate them the most. Figure 3-8 describes the basic Hexad of user types and their motivators. Each user type includes six mechanisms of feedback/reward that are most likely to motivate the user; this can inspire new ideas and build engaging gamified solutions for different users. For example, Achiever may be motivated by “challenges” to test their knowledge and allow them to apply it, such as puzzles once the user has completed a puzzle they feel they have earned their reward/achievement. Marczewski’s model of gamification user types was chosen to evolve it from the existing research at Ulster University that used the user types in an e-learning context. Another reason is to investigate the use of the Hexad in a rehabilitation context.

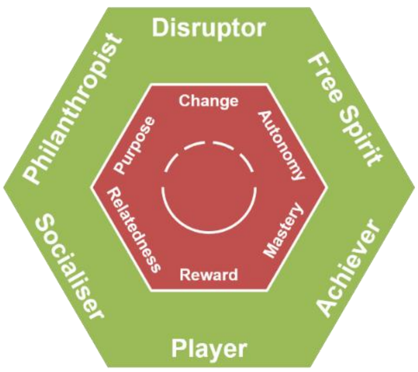



**Figure 3-8: Marczewski's proposed hexad of user types and motivators for a gamified solution**

### 3.6.4 BEHAVIOUR CHANGE

There has been a wide usage of behaviour change theories in society attempting to change an individual’s or groups destructive behaviours towards a more positive and less harmful behaviour. As there is a considerable number of behaviour change theories available for application to different contexts, it is important when deciding which approach to use to be aware of the problem behaviour and the new behaviour to be achieved this will help narrow the theories that would be useful. Some of the core behaviour change theories that might prove useful for improving adherence to rehabilitation in stroke patients include but not limited to (Michie *et al.*, 2014):

a) Control theory (Carver and Scheier, 1982) – proposes that behaviours maintained by a negative feedback loop, the person's perception of their current state is compared against a goal state (targeted behaviour).
b) Feedback intervention theory (Kluger and DeNisi, 1996) – explains how feedback on performance can influence the person’s behaviour and describes how the elements that determine if feedback is negative or positive on the person performance.
c) Health behaviour goal model (Maes and Gebhardt, 2000) – proposes that behaviour change is likely to happen if the target behaviour is compatible with what the person finds important and the things that person wants to achieve in life.
d) COM-B theory (Michie, Maartje M van Stralen and West, 2011)– identifies behaviour as part of a system of interacting elements that involves capability, opportunity, motivation. For a behaviour change to occur, there must be the capability and opportunity to engage in the behaviour, and a stronger motivation than its competing behaviours to engage in the behaviours.

A more recent approach to behaviour change is the Behaviour Change Wheel (BCW) (Michie, Atkins and West, 2014). The BCW was developed from 19 other frameworks identified in a systematic review. It is used as a systematic guide to intervention design for behaviour change by choosing relevant functions and delivery methods to meet the desired target behaviour. The BCW consists of three layers (Figure 3-9), at its core layer is the COM-B (**C**apability, **O**pportunity,

**M**otivation and **B**ehaviour) theory. The COM-B model identifies that behaviour is part of an interactive system involving all COM-B components (Figure 3-10). Behaviour change interventions may need to change one or more of the COM components to target a positive behaviour change. **C**apability explains the physical and psychological capacity to perform the behaviour. Physical includes the skill, strength and stamina. Physiological capability includes the knowledge and skills to perform the behaviour, and the capacity to engage in the thought process. **O**pportunity defines the extrinsic factors that prompt the behaviour or enactment of the behaviour. This includes the physical opportunities created by the physical environmental factors and social opportunities created by the cultural environment. **M**otivation is the processes in a person's brain that energise and direct behaviour. This includes reflective processes (involving evaluation and planning) and automatic process (such as emotions and reactions) (Michie, Maartje M. van Stralen and West, 2011). After analysis of the COM-B to identify the issues in the components, the BCW's second layer offers nine intervention functions to choose from to change each of the components toward the target behaviour. The intervention functions are supported by a detailed taxonomy of Behaviour Change Techniques (BCTs n=93) that help address the COM-B deficits. The last layer identifies seven policy categories that support the delivery of the intervention functions. The BCTs have been used throughout literature. For example, they have been used to recognise the methods to increase physical activity and healthy eating, by identifying the possible problems associated with physical activity and healthy eating and applying the BCTs as solutions (Michie *et al.*, 2013). The analysis from the BCW provides a way of mapping this to behaviour change theories including the theories mentioned above.

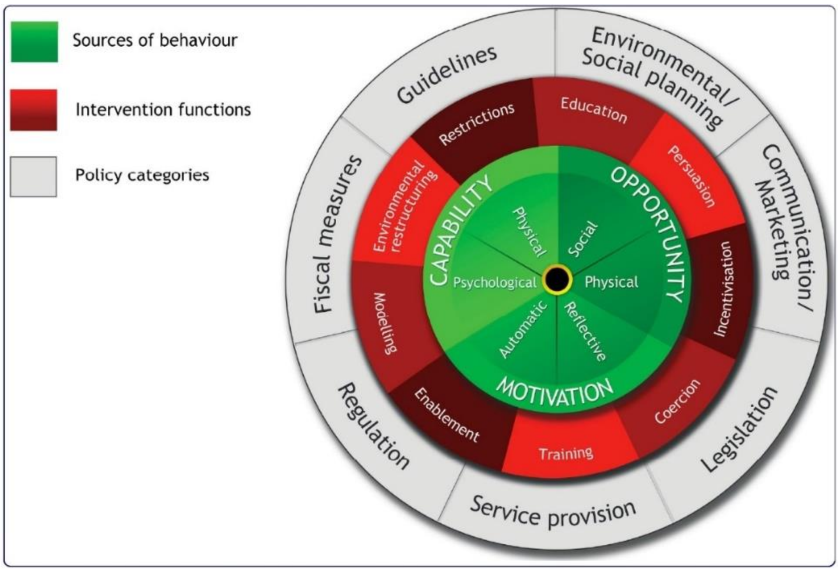



**Figure 3-9: The Behaviour Change Wheel layers for intervention design**

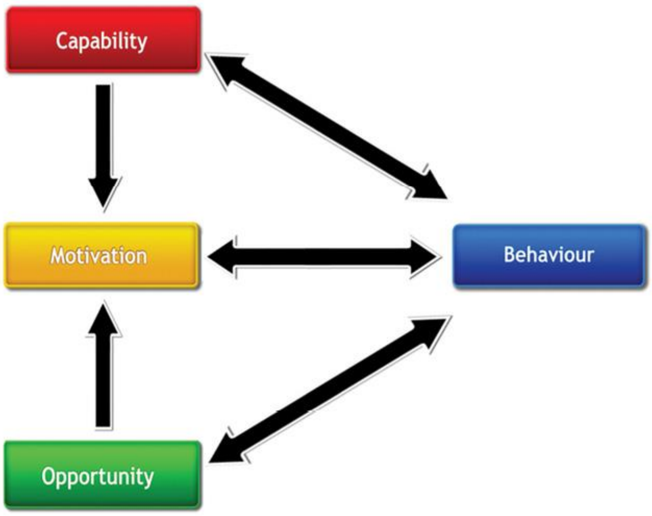



**Figure 3-10: The COM-B theory of behaviours an interactive system involving Capability, Opportunity, Motivation and Behaviour**

### 3.6.5 REHABILITATION GAMING MODEL

The rehabilitation Gaming Model (RGM) contains three core aspects that are mentioned previously above, a gamification typology (Marczewski, 2013), a game design pattern ontology (Bjork and Holopainen, 2004), and a behaviour change framework (Michie, Atkins and West, 2014). This provides a structured approach to designing and evaluating games or gamified solutions for rehabilitation. The gamification typology built into the RGM is Marczewski's Hexad model of motivation for different personality types seen in gamified solutions. The research group has adopted the hexad model effectively in an educational context, and the Hexad seems the most appropriate choice. Bjork's pattern in game design ontology was incorporated into the RGM for its comprehensive approach over the other ontologies with 295 game design patterns included, and it has previously been used in stroke rehabilitation research proving a logical choice for the RGM tool. The RGM utilises the new Behaviour Change Wheel framework, created from 19 other established behaviour change frameworks. The Behaviour Change Wheel incorporates the COM-B model for identifying deficits for targeting positive behaviour change with the provision of BCTs that describe 93 techniques that address the deficits identified from the COM-B.

Using these three models in conjunction, the RGM was developed Figure 3-12 these methods were combined for shaping user behaviour to engage in rehabilitation through capability, opportunity and motivation with game design patterns providing the underlying game design techniques for each gamification user type and their reward and reputation systems. The RGM provides a systematic means of designing gameplay systems suited to player personalities, towards developing a more positive attitude and adherence to rehabilitation exercises. APPENDIX A provides a detailed outline of the RGM model and shows the fusing of each gamification user type and their reward/reputation systems to the comprehensive range of game design patterns, along with the BCTs of Behaviour Change Wheel. Building the comprehensive mapping enables a structured and logical approach to building a gamified application for rehabilitation; providing an insight into aspects of games that directly affect the typical feedback mechanisms of gamified applications with a specific focus on motivations of different people. RGM also highlights aspects of the feedback mechanisms that could promote a behaviour change in individuals who are motivated by different things, thus increasing the possibility of maximising user retention across a population of users.

Figure 3-12 describes the high-level view of the components involved in the RGM; the core component is the game mechanics. The mechanics are designed based on the gamification user types related to the player types component. Similarly, the behaviour change techniques of COM-B are organised to relate to the particular collection of game mechanics and thus related to the player types. The general flow of how the RGM is used for the design of gamified rehabilitation solutions. Firstly, the player interactions with the game mechanics (Dynamics) which results in *feedback* to the player, changing the game state. The player interactions with certain game mechanics determine their player type with feedback being reflective of that particular player type. Feedback to the player can be visual, auditory or haptic given is pivotal to provide a good user experience (Aesthetics). Game mechanics can promote certain behaviour changes according to the challenges from the particular player types interactions on the game mechanics. For example, a socialiser may take part in competition (game mechanic) with other players, overcoming the competition (interact) results in higher points on the high score lists of competitors as a reward (feedback), promoting social comparison as a behaviour change technique. It is possible to use the RGM tool is two ways, firstly, it can be used as a design tool allowing designers to brainstorm and communicate gamified rehabilitation ideas or concepts. Secondly, the RGM can also be used as an assessment tool to evaluate existing gamified rehabilitation solutions, or commercial off the shelf (COTS) games may be analysed to identify games already suitable for rehabilitation purposes. Also, evaluations of games can be conducted during developing and at the end of the development to ensure they provide a motivational and personalised rehabilitation user experience. Initial testing with the RGM as an evaluation tool, five popular commercial games from core genres were evaluated along with three relevant rehabilitation games within the research team. The evaluation involved playing or observing the gameplay and recording game design patterns that link to gamification elements from the RGM. A grading system was determined to quantify the impact on the player types of RGM (Holmes, 2014). Commercial games exhibited at least one dominant player type and as expected all games demonstrated the importance of the achiever player type only fluctuating in the specific design patterns and reward or reputation systems (Figure 3-11 A). The Rehabilitation Gaming system evaluated contained well-designed and entertaining games. However, had a narrow design focus on achievement orientated rewards (Figure 3-11 B), it is maybe natural; that this is the case due to the linkage between goal orientated structures in rehabilitation programs. Arguably, this is a less suitable focus in rehabilitation context as there may be an issue when dealing with failure to achieve the game and rehabilitation goals.

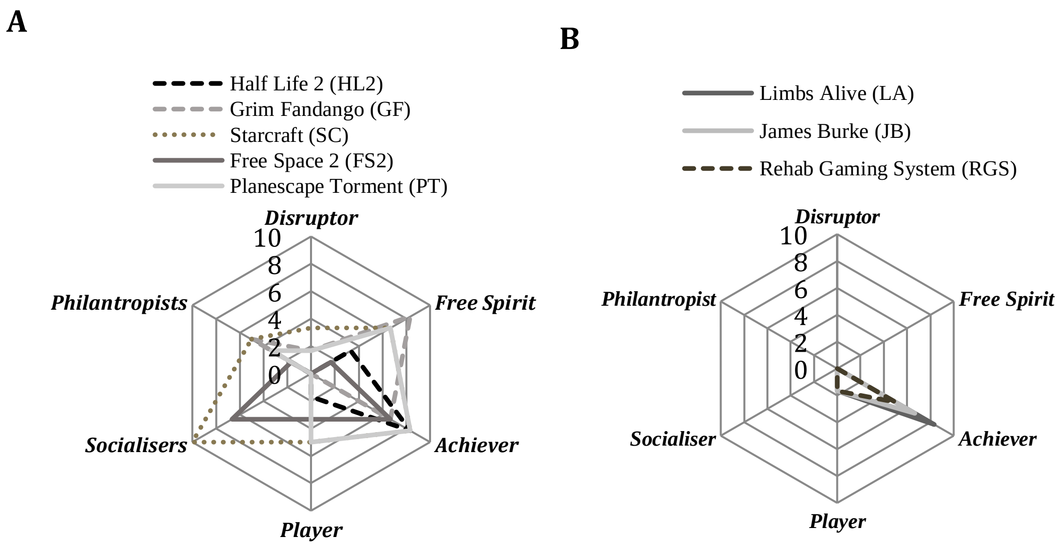



**Figure 3-11: Spider diagrams of the results of the evaluation of commercial (A) and rehabilitation games (B) using the RGM tool**

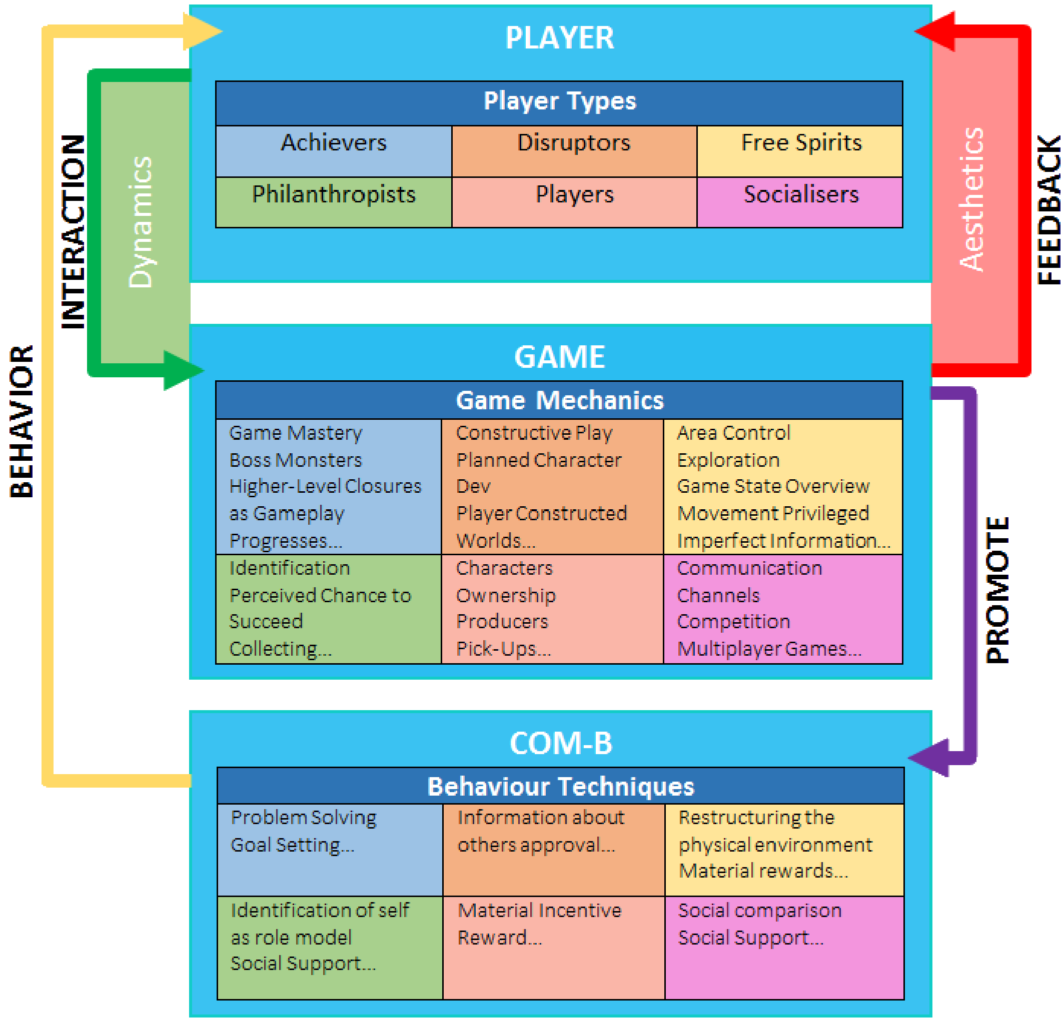



**Figure 3-12: High-level view of how the RGM is used to design gamified rehabilitation solutions**

# 3.7 PROTOTYPE EVALUATION

Our evaluation of the rehabilitation system uses a mixed methods (Creswell, 2007) approach that uses qualitative and quantitative data research methods in all studies of the research. Its premise is that the use of these two methods in combination to provide a better understanding of the research problems than either approach on its own. The mixed methods approach can strengthen the research by offsetting the weaknesses from both qualitative and quantitative research methods. Quantitative is weak in understanding the context in which people behave something that qualitative methods can identify. Qualitative methods can be biased with interpretations made by the researcher or difficulty generalise finding from a large group. Quantitative methods do not have this weakness thus the use of both strengthen each method and the research (Creswell, 2007). Below outlines the prototype evaluation procedure for each of the three studies conducted in this research.

## 3.7.1 EXPERIMENT 1

In the first experiment, able-bodied participants were recruited and received a single structural design using the rehabilitation system for a single session. Participants were asked to perform the movement tasks until they completed all levels of the system. Outcome measures were recorded through questionnaires (APPENDIX E) and semi-structured interviews related to movement performance and usability while the system collected quantitative data on user movement performance for analysis later.

## 3.7.2 EXPERIMENT 2

This experiment used the same approach as study 1 with the prototype modified for improved performance and increased suitability for the recruitment of upper limb impaired participants from Brain Injury Matters, based on user feedback from the previous study, PPI sessions, and clinic and hospital visits. Outcome measures were also similar to study 1 with additional questions added to the questionnaire (APPENDIX J) for assessing usability.

### 3.7.3 EXPERIMENT 3

The final experiment had a multi-use design; able-bodied participants were recruited to play three games that encouraged reach and touching task participation twice a week over a five-week period (session, n=10). Quantitative data was collected on the user's movement performances over each session with a questionnaire (APPENDIX N) and semi-structured interviews conducted during each session to gather information on game design, usability and enjoyment.

## 3.8 CONCLUSION

This chapter outlines the User-Centred Design approach using the PACT framework along with the RGM for designing games or gamified solution that incorporated various motivational characteristics of users to evaluate the research hypothesis. This chapter also outlines the experiments and evaluation methods for each experiment. The next series of chapters describe the design and development of the rehabilitation systems used and the results of the experiments after trials with able-bodied users and upper limb impaired users.

# 4 TAGER: VIRTUAL REALITY UPPER LIMB REHABILITATION SYSTEM DESIGN

## 4.1 OVERVIEW

Target Acquiring Exerciser (TAGER) is a virtual reality (VR) upper arm rehabilitation system. TAGER’s design has evolved from earlier VR research at Ulster (Burke *et al.*, 2009, 2010; Charles *et al.*, 2014) and has been enhanced by the adoption of new improved VR technologies and evolved through reference to state-of-the-art research within the literature. TAGER was developed using a user-centred design methodology, supported by an interdisciplinary PhD supervisory team, and by collaboration with clinicians at hospitals and clinics discussed in Figure 3-4 in section 3.5. TAGER’s custom VR environment and user interface were primarily created to investigate the use of Fitts law (see section 2.3.1.3) for modelling the act of reaching and touching virtual objects within VR. TAGER also investigates the use of the novel Leap Motion Controller (LMC), to track hand motion with high precision and low latency. If Fitts law is applicable within this context, then it could be as part of a system to adapt reach and touch tasks to individual people; personalising tasks to a person’s physiology, capability, and disability.

## 4.2 DESIGN REQUIREMENTS

A number of initial system design requirements were gathered from a number of interdisciplinary workshops and hospital visits before the creation of the initial prototype of an adaptive VR rehabilitation system (APPENDIX Q & R). The below table (Table 4-1) lists the main requirements gathered at this stage.

**Table 4-1: A list of initial design requirements gather through research literature, interdisciplinary workshops and hospital visits.**

| Requirement Description | Type |
|---|---|
| Must include repetitive movements to encourage practice and improve limb function | Rehab Specific |
| Initial inclusion of unilateral movement with bimanual movements to follow later | Rehab Specific |
| Reach and touch task are a good example of common rehabilitation exercises and common movement required for ADLs | Rehab Specific |
| Rest periods should be no more than 60secs to keep the user motivated and engaged. | Rehab Specific |
| Consider high contrasting and soft visuals to reduce the impact of visual issues. | Game Specific |
| Gameplay variation | Game Specific |
| Include various types of cues to investigation impact on feedback and performance; cues include visual, audio & tactile | Game Specific |
| Include feedback on user movement proximity towards the target | Game Specific |

# 4.3 ARCHITECTURE

TAGER incorporates several hardware technologies, to provide interaction, to capture motion data and relay feedback to the user. Figure 4-1 shows the setup for TAGER.


**Figure 4-1: The room and hardware setup**

## 4.3.1 SYSTEM HARDWARE

TAGER utilises several technologies to track and monitor user movements, provide feedback and enable interaction with the VE. The technologies that are implemented into the TAGER system are described below:

a) *Leap Motion Controller* (*Leap Motion Inc*, *USA*) – is a small compact infrared depth-sensing camera that is specially designed and developed to detect the positions and orientations of up to 26 major bones and joints inside each hand of the user, providing markerless motion detection for contact-free natural user interaction. Participants use the Leap Motion Controller in TAGER as the main method of motion tracking and interaction with TAGER’s VR environment to facilitate the reaching and touching of the target objects.

b) *Microsoft Kinect V2* (*Microsoft, USA*)– as with the Leap Motion Controller, the Kinect uses an infrared depth-sensing camera but rather than specialise on hand tracking a Kinect is capable of tracking motion of the full human body. The Kinect tracks all the major body joints positions and orientations including the feet, legs, arms, and head. With TAGER, the Kinect was used to collect data of all joints in the upper body in motion with the goal of investigating the upper body movement when performing reaching tasks. It is natural for a person with upper limb weakness to lean forward to compensate for their limitations in their range of motion or if they are tired. Monitoring the motions may help provide feedback on the guidance of correctness of posture when performing their VR rehabilitation exercises in future systems.

c) *MYO Armband (Thalmic Labs Inc, USA*)– is a wireless, rechargeable control technology for gesture recognition and motion tracking device using EMG and IMU sensors worn on the user's forearm. The use of the Myo armband in TAGER is to collect data to be stored for future studies helping identify changes in muscles, which could highlight factors such as fatigue and correctness of the exercise. The Myo armband also includes tactile mechanisms, for example, vibrations on the skin, which are used to introduce tactile cues into the system.

d) *Oculus DK1(Facebook, USA)* – is a VR headset prototype released by Oculus, the Oculus works by using a 7" screen placed inside the headset that is separated into a pair of identical images side by side, one for each eye. The two images each have a resolution of 640x800 (4:5 aspect ratio). On top of each image, lenses are placed to focus and reshape the images from each eye to create stereoscopic 3D images. The inclusion of the Oculus DK1 headset is to investigate the usability, and the impact VR headset has on user movement performance.

### 4.3.2 SOFTWARE TOOLS

The software for TAGER was developed using Unity (Unity Technologies, USA), a cross-platform game engine capable of developing for most major platforms including Windows, Mac, all modern game consoles and many mobile devices. The majority of applications developed in Unity are written in C# using the Microsoft Visual Studio or Mono develop integrated development environments (IDE). However, it does support other programming languages such as Javascript and Boo. Unity supports both 2D and 3D game development. TAGER is a 3D VR environment coded in C# for a Windows 8 PC or later and the Oculus Rift headset. Key advantages of developing with Unity are that it supports rapid development, there is a large supportive development community, high quality and comprehensive documentation, and there is excellent support for new peripheral devices. The latter facilitated the development greatly for the integration of the Microsoft Kinect V2, Leap Motion Controller, Oculus and the MYO Armband into the TAGER system.

### 4.3.3 TAGER USER INTERFACE DESIGN

TAGER's user environment was deliberately designed to be plain; considering issues that many stroke patients have with distracting objects, maintaining attention on tasks, and having issues with colourful or bright environments. TAGER's 3D virtual environment may be described as the inside of a basic walled room with no wall at the front so users can view the inside of the room. At the beginning of each level, a large red start button on the floor of the room appears, the user is prompted to push the button with their virtual hand to begin the reaching tasks. The reaching tasks consist of the user moving their hand through the Leap Motion's tracking space; the movements are replicated onto a virtual hand in the VE using the hand joint data read from the Leap Motion. The users move through the VE to reach towards and touch the target object, the target object then disappears, and another appears on the floor of the room where the large red start button is located. This object is called the origin; this approach is used to provide consistent movement trajectories. Figure 4-2 show images of the typical movements explained above.

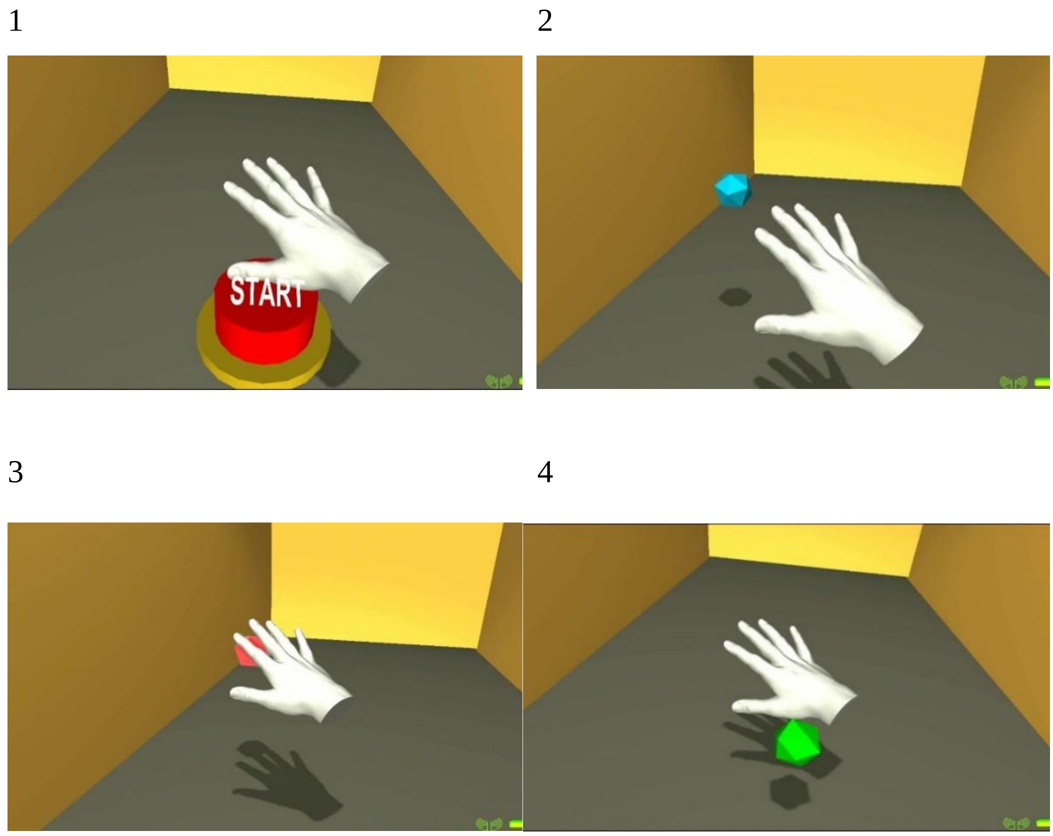



**Figure 4-2: Shows the typical movement steps (1-4) for tasks performed by the participant.**

When the user presses, the large red start button an icosahedron object appears in a randomised location from the 27 pre-defined locations inside the room. The pre-defined locations are organised in cube-like shape to capture data at many locations. The locations are placed at the front (15cm), middle (20cm) and back (25cm) relative to the users forward facing direction, at each depth, there are nine locations positioned from left to right and bottom to top. The locations at each depth are arched the left and right objects are placed in at the same distance from the user. However, the centre objects are placed further back to give a curved effect that accounts for the spherical movement of the user’s arms. Figure 4-3 shows the placement of the locations for the icosahedron objects in the curved cube-like shape. All objects are intentionally placed at fixed locations and at fixed distances from the user’s view to simplify analysis. During the experiment the scale of the target objects change between three different sizes (Figure 4-4) for investigation of their impact on user performance, this is explained further in section 8.3.4. The sizes of the targets are 2cm, 3.5cm and 5cm, this had to translate the metrics units to Unity’s unit of measure. By default, in Unity one unit of measure equals approximately one meter in the real world. In Unity, the size of the objects become 0.02, 0.035 and 0.05 calculated by dividing the real-world object size by one meter, for example, 2cm /100cm = 0.02cm (100cm=1 meter).

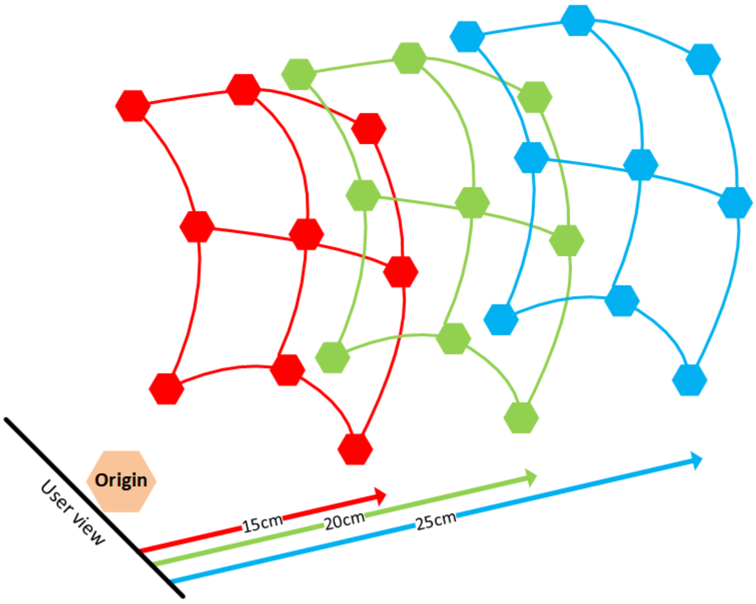



**Figure 4-3: The curved cube-like shaped where each target object was placed in the room and the distance from the user.**

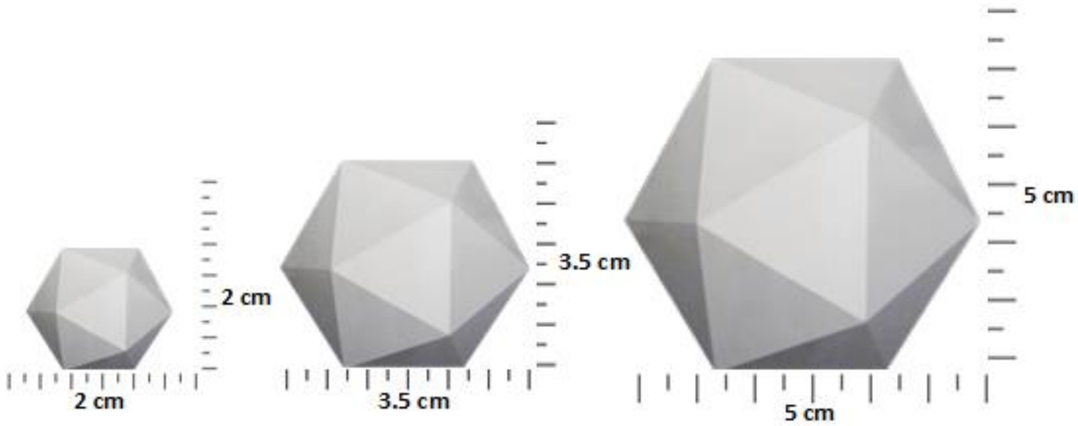



**Figure 4-4: The 3D icosahedron shape and the scales used in TAGER**

TAGER is divided into ten levels with each level consists of four sets of repetitions to control the scene attributes discussed later in section 8.3.4. The inclusion of levels and repetitions is similar to conventional rehabilitation therapy. The clinician will usually ask the participant to complete several different exercises (level) for a period of time or for a number of repetitions (set of repetitions). The levels change the VE attributes; this helps maintain patient familiarity with the process adopted in rehabilitation therapy while allowing the assessment of user performance in each level. The participant is given a 30-second break before continuing to the next level and a 10-second break before the next set of repetitions. Breaks between the levels and sets of repetitions are typical of conventional therapy. The timing for breaks were decided upon based on the feedback from the visits to clinicians, they recommended no more than 60 seconds' break should be given, as patients tend to become less motivated after that time. Each set of repetitions include 27 icosahedron objects that the participant must acquire. For each level, the participant must select a total of 108 (27 repetitions * 4 sets of repetitions) icosahedron objects.

Feedback is particularly important to patients, VR and Gaming systems have the potential to excel in providing rich, informative, personalised, just-in-time responsive feedback. Feedback cues in the VR environment, when appropriately designed, can help users improve interaction performance. Rehabilitation systems have implemented multimodal cues such as visual, tactile and auditory cues (Deutsch Judith E, 2013). The organisation of movement is related to the quality of the viewing environment, particularly visual cues between the user's arm and the objects to improve spatial awareness (Levin, Weiss and Keshner, 2015). Tactile cues have also been reported to improve motor performance (Cameirao, Bermudez i Badia and Verschure, 2008), they are mainly used to help users identify the success of interaction and usually requires contact with the user's skin. Positive auditory cues provide user motivation to perform intensified repetitive tasks, represent temporal and spatial information very well and improving motor learning (Avanzini *et al.*, 2009). The icosahedron shape was purposely chosen as Powell (Powell and Powell, 2014) compared the commonly used shapes in VEs, sphere against a 3D apple and an icosahedron shape. He found that users were finding the icosahedron and apple shaped objects to be faster to select than the most commonly used sphere objects, that have uniform polygons and smooth edges that appear 2D at different viewing angles reducing the amount of spatial information it provides to the user. The low polygon icosahedron provides improved visual cues over the sphere due to the high quality of intra-object surface motion parallax cues, provided by the irregularity of its edges and the occlusion and disocclusion of faces as the viewing angle differs. When touched, the icosahedron disappears, and another icosahedron appears on the floor of the room at the location of the start button. This object is called the origin; this approach is used to provide consistent movement trajectories. All objects are intentionally placed at fixed locations and at fixed distances from the user's view to simplify analysis.

## 4.3.4 DATA LOGGING

Data is recorded and stored about the user’s movements and target acquisition, data logging happens in two main ways:

1. Continuous data logging records motion data of the user's upper extremity including arm and hand joints throughout each user session. Data is recorded at a rate of one-tenth of a second and includes the Leap hand position, as well as the Kinect's positional tracking data of arm joints and calculated arm length. Also, the Myo's raw data is recorded and stored from its EMG sensors.
2. When a user selects a target, first several parameters are calculated and stored, including the user’s starting location, target collision location, distance to the target, movement time, index of difficulty, hits, hand loses and the calculated Fitts Law results.

Data are stored in the computer's hard drive into comma separated value (.csv) files ready to be analysed later.

## 4.3.5 SYSTEM HARDWARE AND SOFTWARE COMMUNICATION

Seamless communication between the hardware and software of TAGER is important to ensure a user-friendly experience. For this reason, it is important to check that all devices are connected, and data is being received. Once all devices are connected, the system will set up a level with which the users can interact. Each level consists of different attributes such as object size, object position, and cues and these are discussed later in Chapter 8.3.4. Interaction is then enabled for the Leap Motion Controller allowing the system to listen for any collisions between the user's virtual hand and the target object. If a collision is detected, the necessary information is stored in CSV files. Motion tracking data from the Kinect and MYO is continuously stored when interaction is enabled. After each level is complete, the user is given a rest period of 30 seconds to alleviate any fatigue incurred, once the rest period has ended a new level is set up automatically by TAGER. This repeats until all levels are completed. If the system detects any hardware failures during the session, the system will stop all processes and will notify the user on the screen, until the hardware devices are reconnected. Figure 4-5 shows an illustration of the communication and management process of the hardware and software in TAGER.

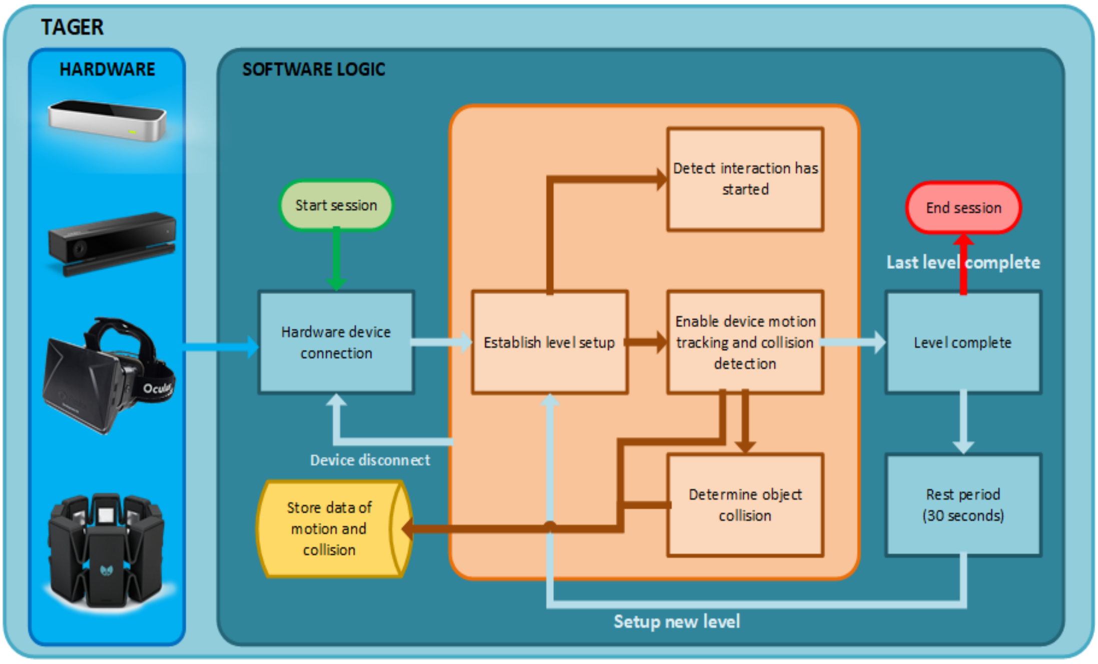



**Figure 4-5: TAGER's integration and management of the hardware and software technology processes.**

## 4.3.6 TAGER'S ADAPTIVE SYSTEM

In TAGER, the information gathered will allow an investigation into creating an adaptive system that will adapt the difficulty of reaching and touching tasks for an easy to use interfacing device for disabled users. One of the well-noted adaptive techniques in the user interface community is Fitts Law. Fitts Law aims at modelling the user movement skills by predicting the amount of time taken to reach and hit a target at a given distance and size. It states that a target further away from the user and smaller should be more difficult to hit than a target that is larger and closer to the user. Researchers have investigated Fitts law and proposed a variation of the original equation to better model user motion with HCIs for 1D, 2D and 3D tasks. Using linear regression and Fitts Law, it is possible to dynamically recalculate the parameters of Fitts Law and infer information about the user's arm movement performance and adapt the difficulty of the movement task. All the relevant information gathered that is required to calculate Fitts Law and its variants are calculated by TAGER and stored for analysis later. This version of TAGER does not apply the adaptive techniques to adapt the difficulty; it collects the information for later analysis. This information is used to investigate the most appropriate Fitts law equation that accurately models the movement of users' with upper limb impairment. Figure 4-6 illustrates the actions that the user takes in TAGER and the stage at which information is collected, calculated and stored for investigation later.

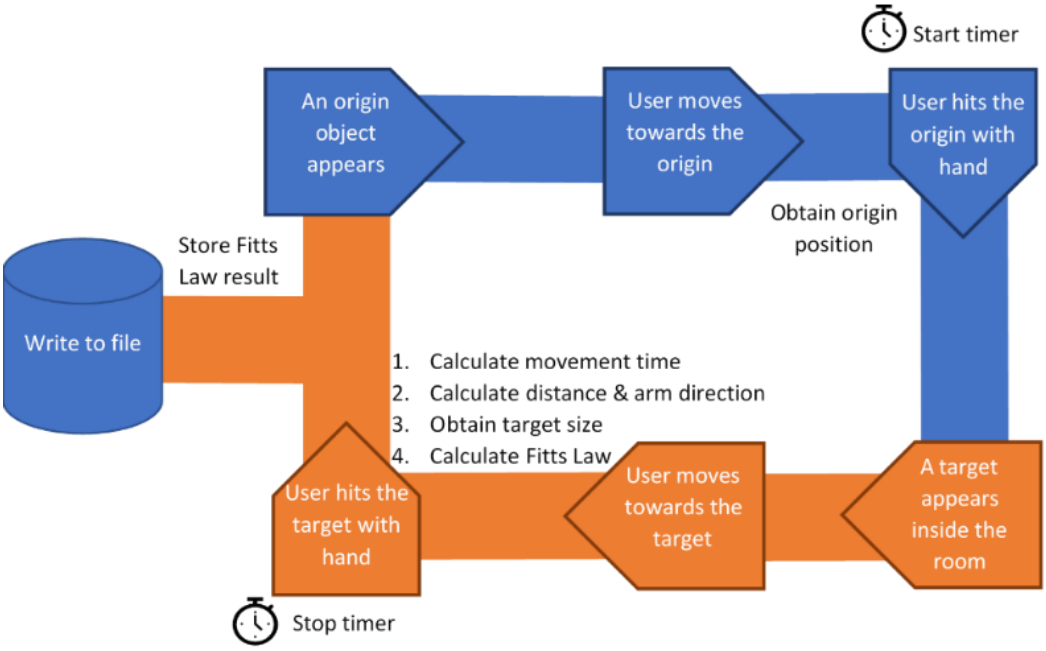



**Figure 4-6: Feedback loop of the actions taken by the user and the stages that TAGER collects, calculates and stores information on Fitts Law**

# 5 EVALUATING TAGER WITH ABLE-BODIED PARTICIPANTS

## 5.1 CHAPTER OVERVIEW

This chapter presents the main findings from the first study with able-bodied participants before conducting experiments with upper limb impaired participants. TAGER is evaluated for its usability as a reaching exercise for rehabilitation. This chapter also discusses the development and evaluation of a user movement profiler based on Fitts Law for quantifying movement performance in reach and touch movements.

## 5.2 AIM AND OBJECTIVES

The overall aim of this experiment was to evaluate the TAGER system with able-bodied users so that its design could be improved before using in a subsequent experiment with stroke patients.

This experiment had two main objectives:

1. Investigate the usability, acceptability, and technical performance of the first prototype of TAGER to provide reaching and touching rehabilitation exercises.
2. Investigate the suitability of Fitts law for modelling user movement within reach and touch tasks in a natural user interface while using the Leap Motion Controller to track hand movement.

Experimental data were obtained quantitatively via recorded tracked user data within TAGER, and qualitative data were obtained from questionnaires and semi-structured interviews.

# 5.3 METHOD

## 5.3.1 EXPERIMENT DESIGN

This experiment had a single use structural design and was approved by the university’s research ethics committee. The experiment was carried out in a private room on the Coleraine campus of Ulster University. The room had the same location and equipment set up for every participant to prevent any variabilities in the experimental procedure.

## 5.3.2 PARTICIPANTS

Able-bodied participants were recruited to evaluate TAGER’s user movement profiling capability, usability, and system reliability ahead of a subsequent study with upper limb impaired participants. Eligibility for this study is shown in Table 8-1. Only Adults (18+) were eligible, who had a completely independent range of movement of their fingers, hands, arms, shoulders, neck, and head. Participants who are suffering from vision problems such as blurred vision, double vision, light sensitivity, colour distortion or depth perceptions issues that were unable to be corrected by spectacles, were excluded. Information about the participant's eligibility was obtained through a pre-assessment demographic and inclusion questionnaire (APPENDIX B) given before their agreed involvement in the study. Participants were recruited from students and staff at Ulster University. Initially, emails were circulated throughout the university to recruit participants along with scheduling information sessions to recruit more volunteers. Volunteers that agreed to participate in the study from the email or information sessions were given an information sheet (APPENDIX D), consent form (APPENDIX C) and demographic and inclusion questionnaire prior to their participation in the study. Once consent was given, and the volunteer was eligible for the inclusion questionnaire, a date and time was agreed to begin the experiment.

**Table 5-1: The eligibility criteria for the study**

| Inclusion Criteria | Exclusion Criteria |
|---|---|
| Males or Females ≥ 18 years old<br><br>A complete independent range of movement of their fingers, hands, arms, shoulders, neck, and head. | Suffering from vision problems such as blurred vision, double vision, light sensitivity, colour distortion, depth perception issues<br><br>Unwilling or unable to consent. |

## 5.3.3 HARDWARE AND SOFTWARE

TAGER was designed and developed using the Unity 5.6 game engine. For this experiment, TAGER ran on a DELL, 64-bit Windows 8.1 laptop with Intel Core i5 @ 2.5 GHz, 8GB RAM, and 500GB hard drive (DELL, USA). A Microsoft Kinect camera was mounted on top of a monitor to record user kinematics. A Myo armband was also worn by the user to measure and record electromyography readings during user movement. The Leap Motion Controller was used as the main interaction with the VE and was placed on the desk with the infrared cameras facing upwards. It was placed 3cm from the edge of the desk to give the user an unobstructed interaction with the VEs. This experiment uses two viewing mediums, a 22" monitor at (1920x1080) resolution and an Oculus Rift DK1. The viewing mediums are described below. Figure 5-1 shows the experimental setup.

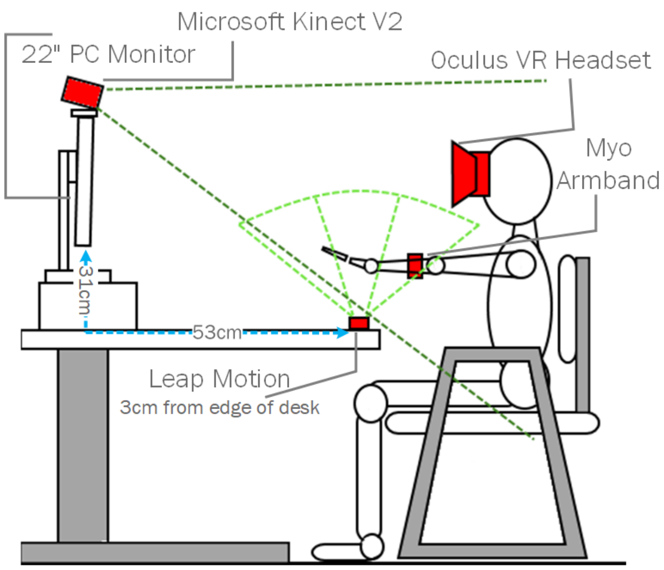



**Figure 5-1: TAGER's experiment setup**

## 5.3.4 EXPERIMENTAL SETUP

The experimental process comprised of three stages:

1. *Training* – participants first went through a training phase using the hardware and software for a ten-minute period that was monitored and controlled by the investigator. It was particularly important to have a training phase due to the novelty of the VR technologies and environment, as this may be the first experience of VR for many of the participants. It is expected that the Leap Motion Controller is an especially novel input device for most people, and so it is important that users learn how to use the technology before beginning the actual TAGER trial. Within training, participants practised the same interactions that they would be expected to perform in the trial to make the learning efficient.
2. *Official TAGER* – After training the participants were given a two-minute rest period to alleviate any tiredness experienced before beginning the full TAGER trial. Tasks within the TAGER VE where divided into ten levels, each level contains four sets of repetitions containing 27 icosahedrons (Figure 4-3) for the participant to target all at different locations, per level there are a total of 108 (4*27) targets with an overall total of 1080 target over the ten levels (108*10) (see Figure 5-2 for illustration):
    a. The first and last levels were purposely designed to be identical to facilitate analysis of the participant's variation in performance over the course of the session. Data analysis included investigation of any effects on performance including fatigue, learning effects, and tactical movement behaviours.
    b. Levels 2-9 were randomised per user to eliminate potential bias in the ordering, a rest period was given between each level (30secs) and repetition (10secs). Each of these levels was unique in that they comprised different combinations of scene attributes:
        i. Visual cues – consist of shadowing and proximity colour change. Light in the VE was positioned carefully so that shadows of the target objects and the shape of the hand was projected onto the floor of the VEs. Proximity colour changing of the target objects was activated when the user's hand was close to colliding with

the target objects. Visual cues were implemented to evaluate their impact on the user's performance and depth perception.

ii. Tactile cues – the Myo Armband includes functionality to vibrate. In TAGER the vibration on the Myo was activated on the user's forearm when the user successfully collided with a target object. Tactile cues were used to provide immediate feedback on target acquisition.

iii. Target scale – object scaled accordingly as 2 (small), 3.5 (medium) and 5cm (large). Objects are scaled to discover the impact it has on cues. For example, larger objects are expected to give greater clarity to visual cues and thus quicker arm kinematics.

Investigating variations of these scene attributes helped build a better understanding of the impact they have on arm kinematics, spatial awareness, movement speed, and accuracy. In two of the randomised levels, the investigator asked the participants to wear the Oculus VR headset to later compare the VR headset against the standard computer monitor and how it impacts performance.

3. *Discussion* – after participants completed the experiment they were invited to participate in a semi-structured interview with the investigator. This discussion aimed to gather user feedback on their experiences of using the technology; collecting information on their perception of performance and their views on TAGER's usability. This process enabled the investigator to informally probe specific negative or positive feedback by encouraging participants to express themselves freely. All participant feedback was recorded on a digital audio recording device for later analysis.

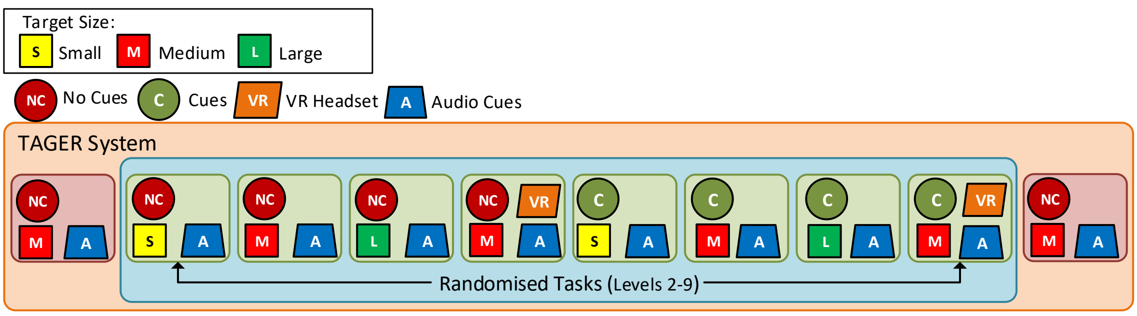



**Figure 5-2: The different scenarios that the participant experienced when performing the interactions in TAGER.**

# 5.4 RESULTS

Participants (n=26) were recruited for the study as detailed above, comprising 16 females and ten males with the mean age of participants being 34 years old. Table 5-2 contains participant demographic information, knowledge of their prior use of games and weekly computer usage (PC hrs), and there use of natural user interface (NUI) devices. NUI devices promote intuitive, natural interaction related to human movement behaviour. NUI can require learning if participants are not familiar with devices such as the Microsoft Kinect, Leap Motion Controller, and PlayStation Eye Toy. The information in Table 5-2 may inform a deeper analysis of results. Of the 26 participants that took part, 23 of the participants were included in the data analysis. Three participants were excluded due to missing data or system issues (loss of tracking). The average amount of time it took for participants to complete the TAGER experiment was 52 minutes. User data was recorded as they performed reaching tasks from an origin to touch a target at various distances and for different object sizes.

**Table 5-2:Participant demographic, game and computer use characteristics.**

| User | Gender | Age | Hand | Games Genres Played | Time Playing Games | Prior NUI Use | PC hrs. | Point Device |
|---|---|---|---|---|---|---|---|---|
| 1001 | F | 20 | R | Board, Casual | Once a month | Y | 5 - 15 | Mouse |
| 1002 | F | 20 | R | Casual | Rarely | N | 15- 40 | Trackpad |
| 1003 | F | 42 | R | Puzzles, Board, Casual, Console/PC | Once a week | N | >40 | Mouse |
| 1004 | F | 19 | R | Handheld, Console/PC | Once a month | N | >40 | Trackpad |
| 1005 | M | 24 | R | Puzzles, Casual, Console/PC | Once a day | N | >40 | Mouse, Trackpad, Touch Screen |
| 1006 | F | 22 | L | Casual | Rarely | N | 15 -40 | Mouse, Trackpad |
| 1007 | F | 30 | R | Casual | Once a week | N | >40 | Mouse |
| 1008 | F | 26 | R | None | Rarely | N | >40 | Mouse, Trackpad |
| 1009 | M | 42 | R | Puzzles, Casual, Handheld, Console/PC | Once a day | N | >40 | Mouse, Trackpad |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1010 | F | 22 | R | Puzzles, Board, Console/PC | Once a day | Y | >40 | Mouse, Trackpad |
| 1011 | F | 37 | R | Puzzles, Board | Once a month | N | >40 | Mouse, Trackball |
| 1012 | F | 44 | R | Puzzles, Board, Handheld, Console/PC | Once a month | Y | >40 | Mouse, Trackpad |
| 1013 | M | 24 | R | Casual, Handheld, Console/PC | Once a week | Y | >40 | Mouse |
| 1014 | M | 30 | R | Casual, Handheld, Console/PC | Once a day | Y | 15 -40 | Mouse |
| 1015 | M | 26 | L | Puzzles, Board, Casual, Handheld, Console/PC | Once a day | Y | >40 | Mouse, Trackpad, Touch Screen |
| 1016 | M | 31 | R | Casual | Rarely | N | >40 | Mouse |
| 1017 | M | 50 | R | Puzzles, Handheld | Rarely | Y | >40 | Mouse, Trackpad |
| 1018 | M | 34 | L | None | Never | N | >40 | Mouse |
| 1019 | F | 66 | L | Puzzle, Board | Rarely | N | >40 | Mouse, Trackpad |
| 1020 | M | 56 | R | Casual | Once a day | N | 15 -40 | Mouse |
| 1021 | M | 44 | R | Puzzles, Board, Handheld, Console/PC | Once a day | N | 15 -40 | Mouse |
| 1022 | F | 46 | R | Puzzles, Board | Once a month | Y | 15 -40 | Mouse |
| 1023 | F | 54 | R | Puzzles, Board | 2-3 times a week | N | 15 -40 | Mouse |
| 1024 | F | 26 | R | Puzzles, Board | Rarely | Y | 15 -40 | Mouse |
| 1025 | M | 67 | R | Puzzles | Once a week | N | >40 | Mouse |
| 1026 | F | 24 | R | Casual | Once a day | N | >40 | Mouse |

## 5.4.1 USER HAND MOVEMENT PROFILING

### 5.4.1.1 EVALUATION OF THE FITTS LAW VARIANTS

Fitts's law suitability to model the user's movement performance is evaluated using several common forms of the equation (section 2.3.1.3). The regression results of each model are analysed and compared to each other. Figure 5-3 and Figure 5-4 show the average regression lines across all participants, fitted to the data from the regression results at the start and the end of the experiment for each of the Fitts Law equation to summarise and identify any trends over all users. To calculate the regression lines, the gradient and y-intercept coefficient results from each model with a range of fixed index of difficulty, the regression line equation (5-1) is as follows where *m* is the gradient, *x* is the fixed index of difficulty *a* is the y-intercept of the line and *y* is the estimated movement time.

$$y = mx + a \qquad (5\text{-}1)$$

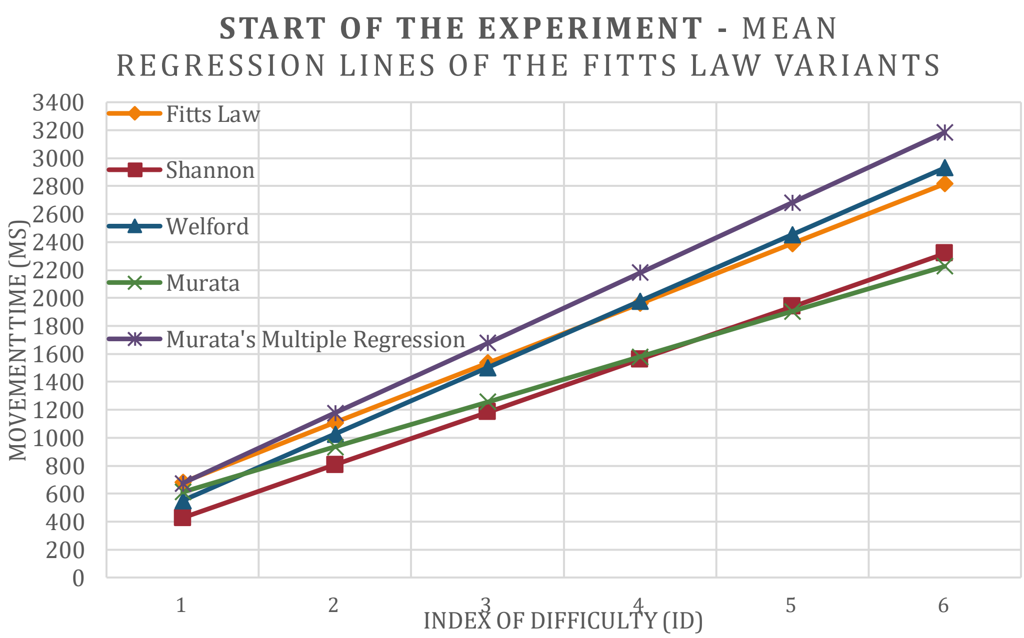



**Figure 5-3: The average regression line from the analysed data at the start of the experiment (first level) with fixed IDs for the five popular variants of Fitts Law across all participants.**

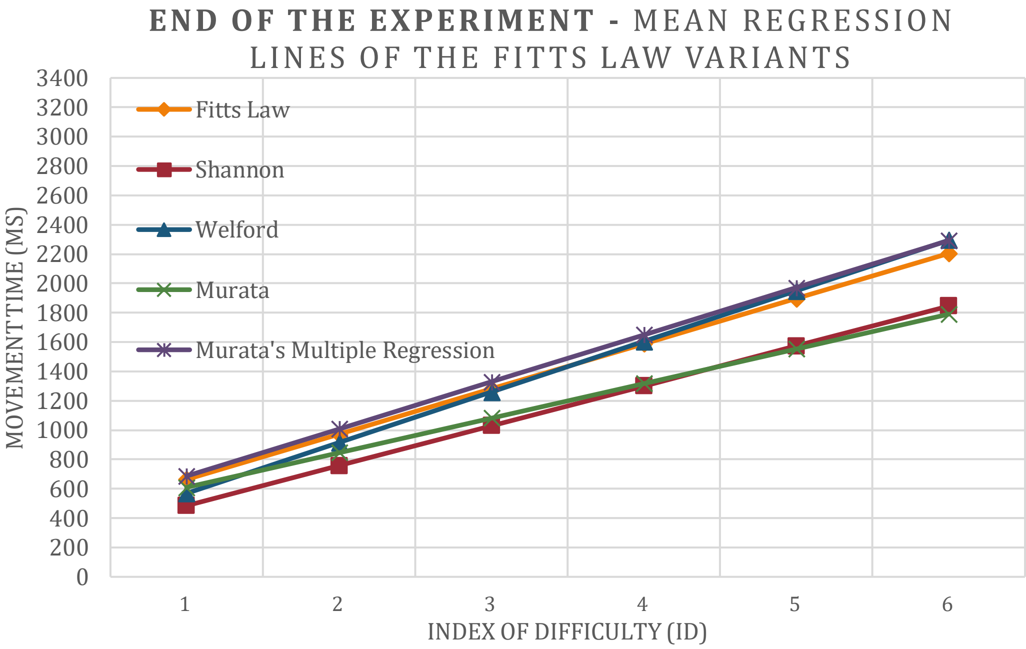



**Figure 5-4: The average regression line from the analysed data at the end of the experiment (last level) with fixed IDs for the five popular variants of Fitts Law across all participants.**

**Table 5-3: Average gradient across the start and end levels for all five variants of Fitts Law.**

| EQ | START (ms) | END (ms) | % Change | START (Bits per sec) | END (Bits per sec) | % Change |
|---|---|---|---|---|---|---|
| (1) | 427 | 308 | 27% | 2.5 | 3.2 | -28% |
| (2) | 378 | 272 | 28% | 2.9 | 3.7 | -27% |
| (3) | 476 | 345 | 27% | 2.3 | 2.9 | -26% |
| (4) | 323 | 236 | 26% | 3.5 | 4.2 | -20% |
| (5) | 502 | 321 | 36% | 2.1 | 3.1 | -47% |

Table 5-3 shows the average regression line gradient values for all participants. Each Fitts law equation applied is compared between all user data at the start and end of the experiment. By the end of the experiment, regression line gradient values consistently reduced for all equations, the reduction in regression line gradient shows that the difficulty of the tasks (ID) had less impact on movement time, indicating that users were learning to improve their performance of the reaching and touching exercises with practice. Monitoring changing gradient along with the fitness of the regression line ($R^2$) may be useful measures for evaluating user performance over time. A reduction of the regression line gradient may be due to reduced learning effects and improved movement capabilities (over a longer period), while an increase in regression line gradient might indicate fatigue (over a shorter period). By the end of the experiment, all equations provided y-intercept values ranging from 213 to 374ms (initially a wider range of 172 to 740ms). Though these values are only loosely correlated to human movement response (typically 200 to 300ms for healthy adults) the common change in response time after practice suggests that participants had potentially improved their movement response to the appearance of the target objects. Although all forms of Fitts Law have similar results, the multiple regression application of Murata's equation (2-4) explained in section 2.3.1.3, was chosen for further analysis due to the quality of fit to the data but it also accounted more for reaching and touching in 3D space. At the start and end of the experiment the $R^2$ values for the multiple regression approach were higher (START - $R^2 = 0.157$, END – $R^2 = 0.131$) than any of the other equations analysed (Table 5-3), and thus for a given ID it is more likely to provide more accurate prediction of user movement time. Figure 5-5 shows the comparison of Murata's multiple regression lines at the start and end of the experiment.

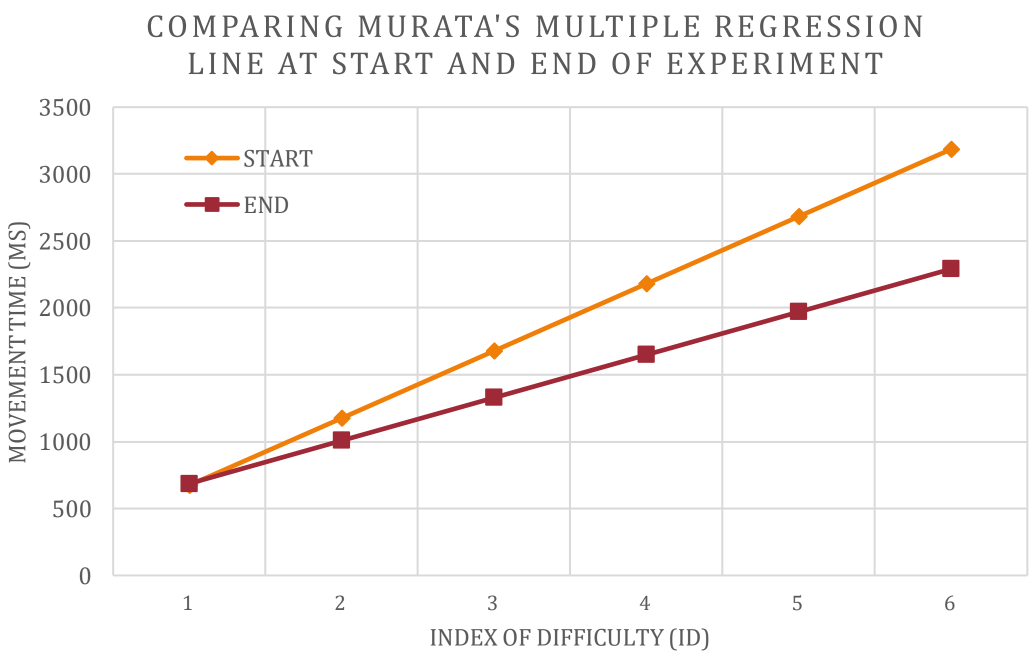



**Figure 5-5: The average regression line comparison of Murata's multiple regression at the start and end of the experiment across all users.**

### 5.4.1.2 PARTICIPANT OVER TIME PERFORMANCE ANALYSIS

The nature of this experiment was fundamentally exploratory; to develop a user profile that could help understand how best to create an adaptive VR system that can personalise interactive movement tasks for individuals or reaching and touching exercises. The profile developed may allow systems to dynamically change properties of interactable objects, such as distance from the user, the scale of the object, and the angle from the user, based on the user's movement capabilities. In principle, this approach can be applied to movement zones in 3D coordinate space. This may be beneficial to identify weaknesses in the person's range of movement and provide a focused and personalised rehabilitation for the user. The proposed profile uses regression analysis of Fitts's Law to determine the relationship between user movement time and the difficulty of the reaching task, descriptive statistics of the residual of the regression line to explain the distribution of the user's movement times, and target acquisition performance to help explain the quality of the user's movement. Below in Table 5-4 are the outcome measures of the profile and how they explain the user's movement.

**Table 5-4: The statistics used to build the user profile for explaining the user's movement**

| **Data statistic** | **Description** |
|---|---|
| Regression statistics | |
| R2 | A measure of how close the data is to the fitted regression line showing how predictable the user's movements are during the tasks, values lie between 0 and 1, a value of 1 states the user's movement was 100% predictable. |
| Gradient coefficient (b) | The steepness of the regression line, a steeper regression line gradient identifies that the user was finding the task more difficult and a shallower suggests the tasks where easier. A negative regression line gradient shows values of low ID were more difficult for the user. |
| Y-intercept coefficient (a) | Where the regression line crosses the y-axis, this could be a measure of the user's reaction time. |
| Sin coefficient (c) | The sin coefficient is the coefficient of sin(θ), a higher value states that the angle required by the user to move |

| | |
|---|---|
| | towards a target had a bigger impact on how difficult the task was. |
| Performance statistics | |
| Standard deviation | How spread out the movement times are from the regression line as a potential indicator of the user's accuracy of movement |
| Kurtosis | Detection of occasionally high movement time. Is a possible indication of erratic or uncoordinated movement |
| Skew | The symmetry of the movement time along the regression line, a positive skew indicates faster movement times, and negative suggests slower movement times |
| Performance statistics | |
| Hits | Number of successful hits that the user has selected with their virtual hand |
| MeanMT | Mean movement time taken by the user to select a series of target objects. |

TAGER’s experimental design implements two identical levels one at the beginning and end of the experiment, enabling investigation over time for potential learning effects indicated by improved performance or user fatigue resulting in performance decline. Table 5-5, provides a profile of average performance statistics across all users at the start and end of the experiment, consisting of parameters for regression data that explains the relationship between the user movement time and the difficulty of the task (ID) and also the fitness of the regression line for predicting future user movement time for adapting difficulty. The profile includes descriptive statistics on the residuals of linear regression that describes the variation of the user’s movement times along the regression line and the inclusion of objective performance measures in the profile may provide insight into user target acquisition in the VEs. Mean MT’s across all users for the start of the experiment was 1400ms, by the end of the experiment Mean MT was 1208ms; a 12.88% decrease in mean movement time. Despite having a 10-minute training session before the official trial, user movement time performance still significantly improved over time (T=2.07, DOF=22, p=6.29E-04), this suggests that it is possible users required more time to learn the actions. The number of hits is an informative measure, and capable users can be noticeable from the weaker performing users. The maximum amount of hits a user could receive was 1080, all of the participants recorded hits above half (540) of the total hits. The lowest hits were 634 and the highest being 1000, the average total hits recorded was 854. The mean hits from all users increased from 82 at the start to 86 at the end of the experiment, from a possible total of 108 hits. By the end of the experiment user target acquisition improved by 7.42%, this was a significant improvement (T=2.07, DOF=22, p=3.84E-02). Regression statistics such as the gradient and y-intercept were talked about previously in the above section and showed that on average users had a more gradual regression line gradient with a 36% decrease by the end of the experiment and intercept remained around the norm for human response time by the end of the experiment. Additionally, by the end of the experiment, the $R^2$ of the regression line did decrease by 2.6%, explaining less of the variability of the movement time. However, the change in $R^2$ was not significant. Additional information can be gained from descriptive statistics of the residuals of the regression, to explain users' movement performance further. Mean standard deviation decreased by 6.75% suggesting user movement accuracy did improve; the small improvement of the standard deviation may be explained by the 145.21% increase in positive kurtosis, with some data points deviating further from the regression line. Mean skew increased by 47.04% (positive value) indicating that the majority of user movement times were faster. A higher positive kurtosis may be explained by the user occasionally overshooting the target and having to correct their movement trajectory, taking more time to acquire the target. This may be indicative of possible fatigue effects. There was no correlation between performance measures and user information such as age and gender.

**Table 5-5: Average performance profiles across all users for the start and end levels.**

| Statistics | Start | End |
|---|---|---|
| Performance statistics | | |
| Mean MT (secs) | 1400 | 1208 |
| T-test P= (0.05) | 6.29E-04 | |
| Hits | 82 | 86 |
| T-test P= (0.05) | 3.84E-02 | |
| Regression statistics | | |
| R-Squared | 0.157 | 0.131 |
| Gradient | 0.502 | 0.321 |
| Intercept | 0.172 | 0.366 |
| Descriptive statistics of the residual of the regression | | |
| Standard deviation | 0.548 | 0.511 |
| Kurtosis | 4.037 | 9.899 |
| Skew | 1.588 | 2.335 |

As discussed earlier, it is possible/likely that users may have still been learning during the experimental tasks despite having a training phase beforehand. This could have been due in part to the novelty of the technologies hardware, the unique type of VEs interactions asked of the user, or that they are novices regarding interactive digital experiences (such as games). It is important that learning effects be identified, especially if performance is not good enough for Fitts law to be applied. In this case, a different adaptive strategy is required, and additional support provided to users to help them improve. A poor regression fit can indicate that a user is still in an early phase of learning how to use the system effectively, assuming that a user’s level of disability has already been accounted for. It is desirable to adapt task difficulty using Fitts Law while accounting for learning effects. However, learning effects may not be the only cause of a poor fit to the regression. In Table 5-6, Nine of the 23 participants that took part had a weak fit to the regression model at the start of the experiment, while at the end of the experiment ten participants had a weak fit to the regression model, though three of the participants were different from the nine identified at the start. These three participants may have been become tired or bored, rather than be incapable, as their regression profiles were good at the start. Thus, it is important to analyse user profiles individually, as effects of learning, fatigue and boredom are personal.

Every person is different, and their movement performance can improve or deteriorate at various times. In evaluating user performance, it is best to consider a user's full user movement profile (see Table 5-6 for examples). $R^2$ and associated P-Value are indicative of the quality of the regression to the data. $R^2$ and P-Values depend on the context and in this case where a novel VR headset, a 3D space, NUI, and using the hand unsupported, the $R^2$ values are expected to be lower than for a mouse pointer activity. Thus, standard deviation, kurtosis and skew statistics are helpful in profiling the user's movement activity.

**Table 5-6: A selection of user regression and performance profiles.**

| User | 1011 | 1016 | 1017 | 1019 | 1026 | 1023 |
|---|---|---|---|---|---|---|
| **Start**- Descriptive | | | | | | |
| Standard Deviation | 0.508 | 1.087 | 0.402 | 0.447 | 0.622 | 0.583 |
| Kurtosis | 4.422 | 7.662 | 1.625 | 2.469 | 1.269 | 2.881 |
| Skew | 1.791 | 2.394 | 1.173 | 1.454 | 1.213 | 1.387 |
| **End**- Descriptive | | | | | | |
| Standard Deviation | 0.844 | 0.543 | 0.548 | 0.519 | 0.411 | 0.425 |
| Kurtosis | 18.483 | 10.630 | 17.637 | 1.013 | 0.827 | 3.461 |
| Skew | 3.603 | 2.482 | 3.080 | 1.099 | 1.173 | 1.589 |
| **Start**- Regression | | | | | | |
| R2 | 0.090 | 0.029 | 0.303 | 0.289 | 0.133 | 0.219 |
| P-Value | 4.4E-02 | 2.7E-01 | 8.6E-08 | 8.5E-07 | 1.1E-03 | 6.3E-06 |
| Intercept (a) | 0.412 | 0.865 | 0.252 | -0.509 | -0.073 | -0.409 |
| Gradient (b) | 0.294 | 0.324 | 0.145 | 0.817 | 0.393 | 0.795 |
| Sin coefficient (c) | 0.316 | 0.507 | 1.146 | 0.103 | 0.715 | 0.446 |
| **End**- Regression | | | | | | |
| R2 | 0.077 | 0.168 | 0.084 | 0.324 | 0.078 | 0.379 |
| P-Value | 8.2E-02 | 2.3E-04 | 1.2E-02 | 1.0E-08 | 3.2E-02 | 9.5E-11 |
| Intercept (a) | -0.243 | 0.577 | 0.673 | -0.743 | 0.274 | -0.645 |
| Gradient (b) | 0.949 | 0.062 | 0.072 | 1.305 | 0.435 | 0.790 |
| Sin coefficient (c) | -1.130 | 1.127 | 0.748 | -0.976 | -0.528 | 0.461 |
| **Performance** | | | | | | |
| Targets Hit (1080) | 767 | 976 | 964 | 909 | 913 | 1000 |
| Start Hits | 69 | 92 | 93 | 85 | 98 | 100 |
| End Hits | 65 | 94 | 103 | 97 | 88 | 100 |
| % Change Hits | -5.80% | 2.17% | 10.75% | 14.12% | -10.20% | 0.00% |
| Start Mean Time | 1.294 | 1.914 | 1.292 | 1.500 | 1.262 | 1.645 |
| End Mean Time | 1.307 | 1.386 | 1.269 | 1.713 | 0.957 | 1.375 |
| %Change Mean Time | 1.02% | -27.57% | -1.80% | 14.25% | -24.19% | -16.38% |

Table 5-6 above provides some of the more informative user profiles consisting of parameters for regression data, objective performance measures, and descriptive statistics on the residuals of the regression line, for further analysis and discussion of individual participants (all user profile information is located in (APPENDIX P). User 1011 profile is an example of a person that may have required more VR activity training. After regression analysis, $R^2$ and associated P-Value indicated a weak fit to the model both at the start and end of their activity series. Standard deviation increased suggesting increased inaccuracy in movement. Furthermore, kurtosis and skew increased indicating that the user was overshooting the targets more often. Hits decreased, and movement time increased over time. User 1011 showed signs of fatigue which may have explained poorer results than at the start, though they may also not have felt motivated to complete the tasks. Nonetheless, it would be recommended that this type of user continue to train after a rest period.

User 1016 showed improvement in movement performance over the course of the experiment; he had a poor start producing an unreliable fit to the regression model, high variation in movement and the highest mean movement time (1.914secs) across all users. However, at the end of the experiment, he had become 27.57% quicker (Figure 5-6) while maintaining a consistent number of hits. His regression model became more reliable with a higher $R^2$ and a significant model according to the P-Value. Standard deviation reduced by half and kurtosis increased but this increased kurtosis due to occasionally larger movement times (overshoots) may have had little impact due to the large decrease in standard deviation suggesting he was more accurate more often (Figure 5-7). User 1016 may have still been in a learning phase even after training, explaining why he had a poor start but had learned enough by the end of the experiment that his movement had become more consistent and performant at the end, that task difficulty could be reliably be adapted.

User 1017 had the opposite profile to 1016, starting strong deteriorating towards the end. This user may have become fatigued or lacked concentration, and for people like this, it would be recommended that task difficulty would be incrementally decreased within the activities to investigate if fatigue subsides, if not a rest would be advised.

User 1023 arguably had the most sustained success, having good regression fit both at the start and end of the experiment. Overall target acquisition was the highest among all users (1000), the number of hits at the start and the end of the experiment were equal (100). Standard deviation decreased, and a decrease in mean movement time shows that the user got quicker. Even though user 1023 had a reliable profile at the beginning, they continued to show signs of improvement.

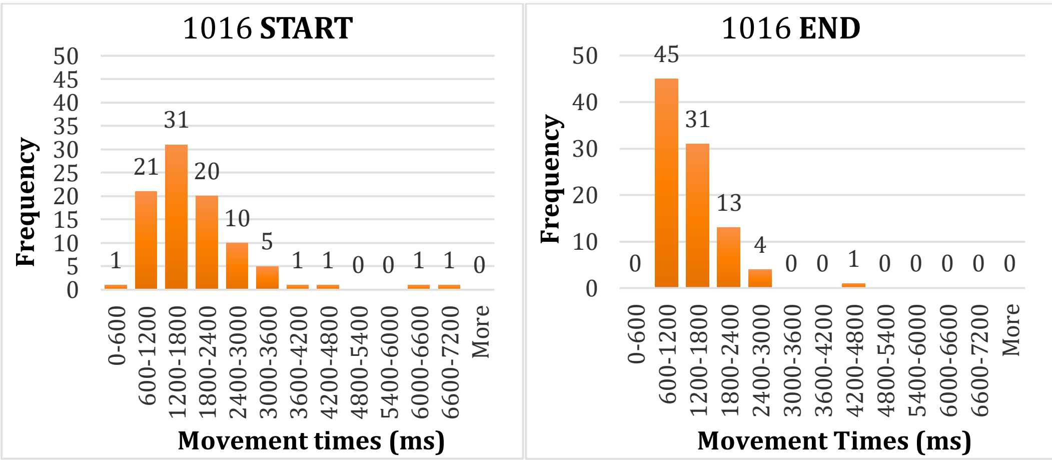


**Figure 5-6: 1016's movement times at the start and end of the experiment.**

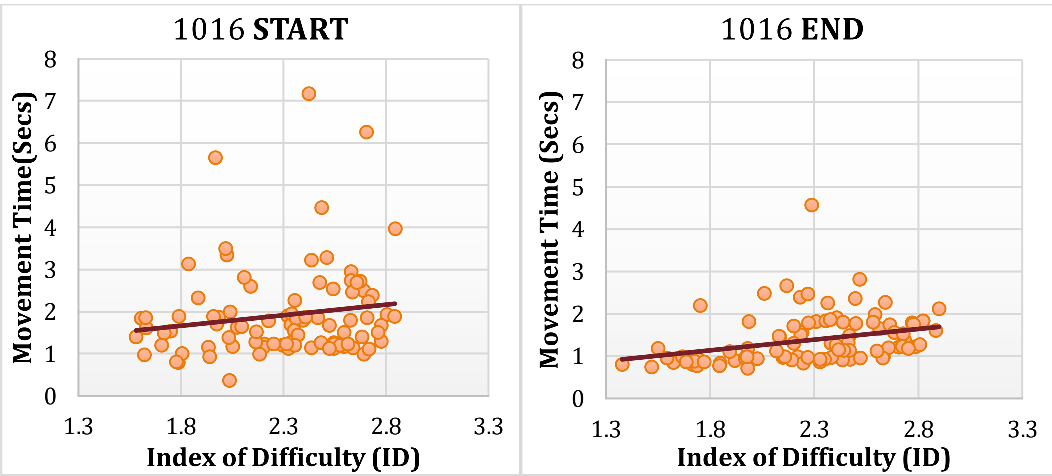


**Figure 5-7: 1016's Murata's multiple regression model at the start and end of the experiment.**

User 1026 is a potentially interesting example, who started well but whose hits significantly decreased yet becoming faster at the end of the task. Descriptive statistics at the end of the experiment showed less variability than the beginning of the experiment, suggesting more effective arm movement. Kurtosis and skew reduced over time, showing less overshooting of the target and movement times were becoming more evenly spread above and below the regression line. A low R2 value at the end of the experiment explained less variance of the user's movement. A lower standard deviation shows that most movement times were closer to the regression line and the skew increasing over-time suggesting more data points below the regression line. However, it seems that the existence of outlier (high movement times) raising the regression line and lowering its predictability (Figure 5-9). Figure 5-8, shows 1026's histograms of movement times at the start and end of the experiment, which corresponds with the user's faster mean MT and most of the time movements were more controlled but occasionally they did record higher movement times. Mean MT dropped by 24.17%, which suggests, concerning the user profile context, that during the end task this user may have adopted a high-risk strategy.

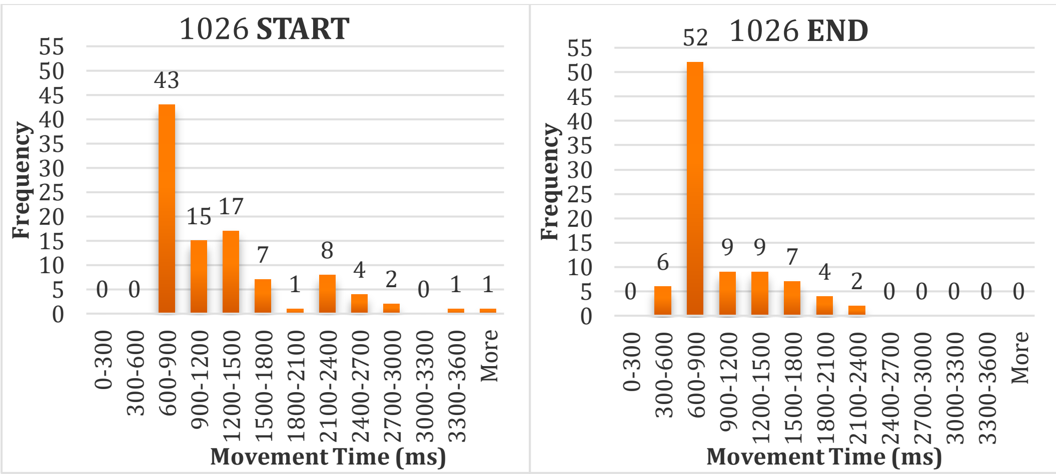



**Figure 5-8: 1026's movement times at the start and end of the experiment.**

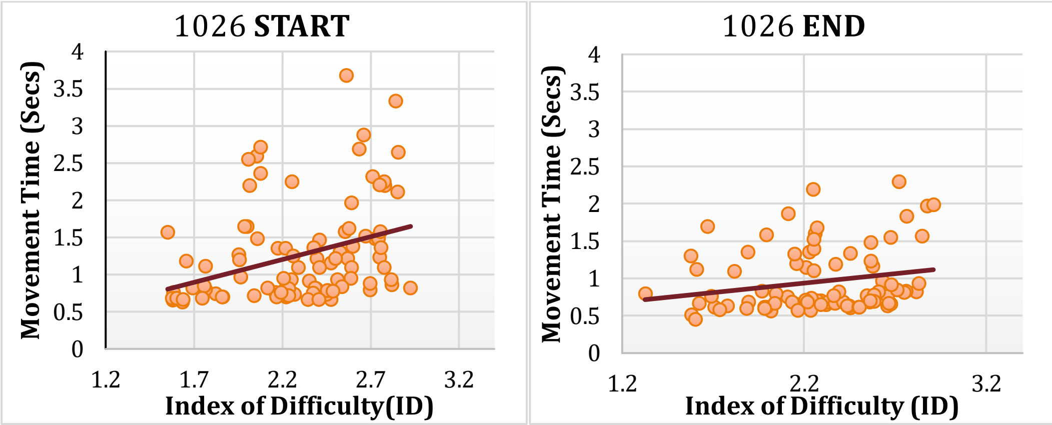



**Figure 5-9: 1026's Murata's Multiple Regression motion model at the start and end of their experiment.**

User 1019 seems to have adopted a tactical approach, moving 14.25% slower improved the user's number of hits by 14.12%. This approach seemed to have improved the likelihood that user 1019 movements correspond to Fitts Law. R2 increased by the end of the experiment with a P-Value that increased in significance, indicating that this result did not happen by chance. Regression line gradient increased, further reinforcing that the user was slowing down when selecting the targets. Standard deviation increases but this was not a significant increase. Kurtosis and skew remained positive and decreased, suggesting that user 1019 had fewer overshoots of the targets. Figure 5-10 & Figure 5-11 shows user 1019 movement time distribution and the regression model for Murata's multiple regression.

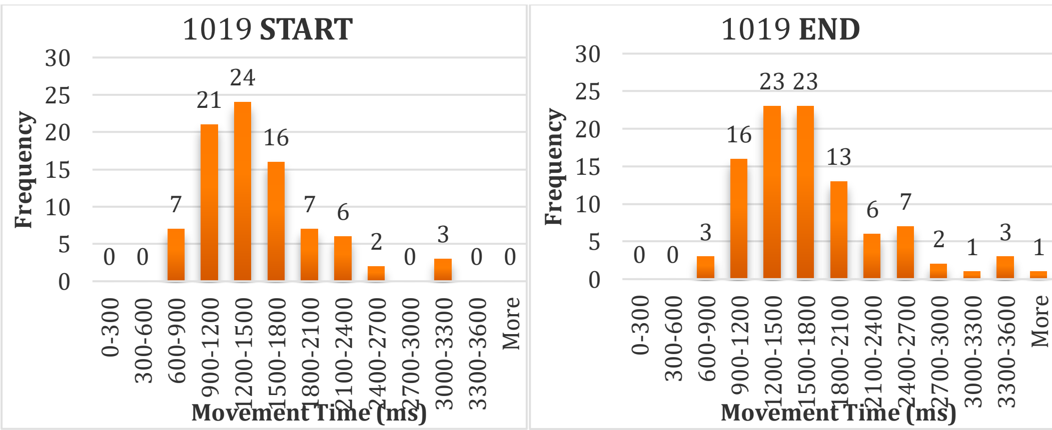



**Figure 5-10: 1019's movement times at the start and end of the experiment.**

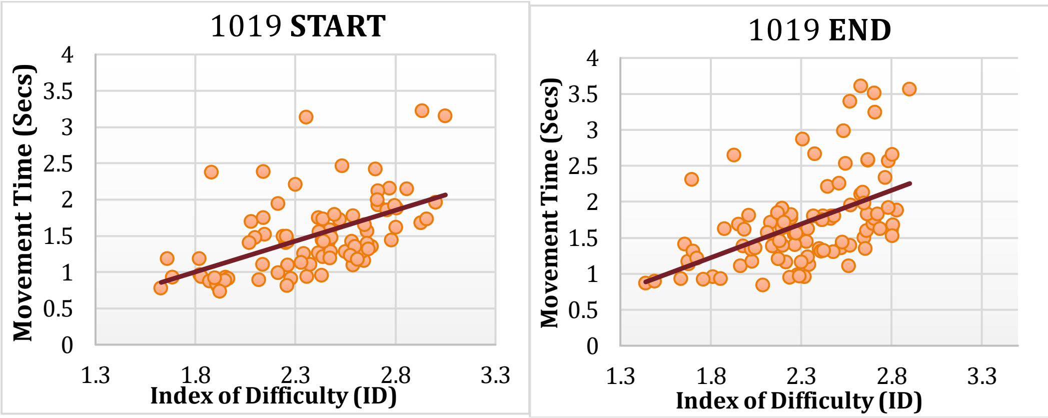



**Figure 5-11: 1019's Murata's Multiple Regression motion model at the start and end of their experiment.**

### 5.4.1.3 EVALUATING THE MOVEMENT ZONES OF THE VIRTUAL ENVIRONMENT WITH THE USER PROFILE

It is not uncommon that people suffering from upper limb weakness following a stroke will have difficulties in specific areas of their range of movement. Physiotherapists and occupational therapist usually assess the patient's range of movement through assessment methods such as ARAT and WMFT discussed in section 1.2.1.1. Usually, the assessments are graded on a scale and recorded objectively by the clinician. It may be useful for clinicians also to know what specific spatial regions a patient is having difficulty reaching towards. It may also be useful for them to have additional information on the user's ability to perform the movement in particular areas of their range of movements such as their movement speed, accuracy, and consistency towards those locations. Within VR, it is relatively easy to divide the VEs coordinate space into zonal areas, relative to the user's 3D spatial range of motion. Within TAGER's VE, the space was divided into 27 movement zones that where arched similar to the object positions in Figure 5-4. From each user's data of the complete experiment and performed Murata's multiple regression on each zone – a total of 40 data points per zone. From the results, the creation of a performance profile for each zone was determined. This enabled analysis of user performance per zone and the potential use of zonal profiles to enhance the adaptive model. From the zonal performance profiles, it may be possible that over time analysis of each user movement zone profile could be performed to identify improvements or deteriorations of user movements towards each zone. This could be useful for adapting the difficulty for individual zones, by adapting difficulty per movement zone it can further personalise the user's rehabilitation by identifying areas of weakness in the user's range of movement and using the zone profile to adapt the difficulty accordingly to focus training in areas that the user finds challenging. For example, if a user is finding it difficult to move towards a certain area, the zone profile is then used to adapt and make the zone easier to continue training in this area. In addition to making the target easier to acquire, it is also possible that when a zone is found to be difficult for the user that the system only places objects in areas of difficulty to encourage the user to train more in the challenging zones.

Considering the experimental user data from a zonal perspective, user 1026 and 1019 zonal profile can be viewed in Table 5-7 & Table 5-8 respectively. The movement zones were labelled as in Figure 5-12 as with positions: depth (F, M or B), sideward (L, C or R), and height (B, C or T).

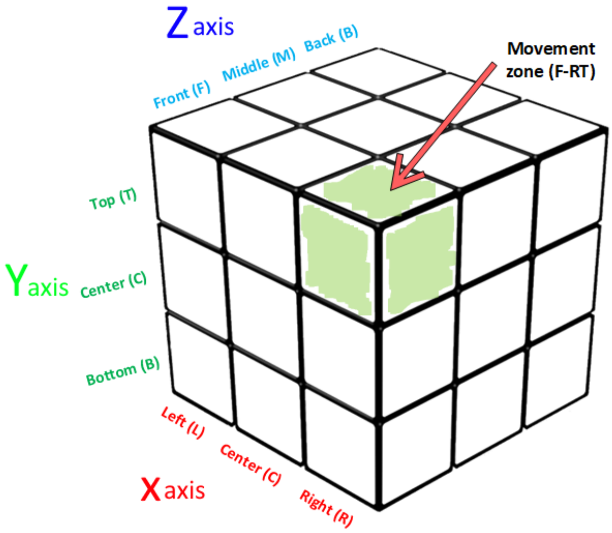



**Figure 5-12: The position of the zones analysed, and the labelling used.**

#### *5.4.1.3.1 USER 1026'S MOVEMENT ZONE ANALYSIS*

Analysis of user 1026's movement zones (Table 5-7) showed that the user found targets placed in the middle depth easiest to acquire; with an average Mean MT that showed a quicker user movement than the other depths. Mean standard deviation and kurtosis of all movement zones at the middle depth was the lowest suggesting the user's movement times were tighter to the regression line and that there were less extreme movement times (potential overshoots). Regression results showed that at greater distances along the z-axis, the regression line gradient increased in steepness with all these zones showing similar results in mean $R^2$. However, the majority of regression line gradient values for movement zones closest to the user on the z-axis recorded a negative value suggesting that the user found the lower index of difficulties more challenging. The average Mean MT for the front depths recorded the slowest movement time, highest standard deviation and kurtosis suggesting a lack of coordination of movement for front depths. Figure 5-13 shows a visualisation of the regressions $R^2$ values that explain the predictability of each movement zone for user 1026. Movement zones that have a lighter colour have higher $R^2$ values. At the front and back z-axis, the majority of the values of $R^2$ where low (black colour) showing that the user could not be accurately predicted by the regression model alone. It would be more important to analyse each movement zone to identify the user's strengths and weaknesses in their range of movement, this is continued in more detail below.

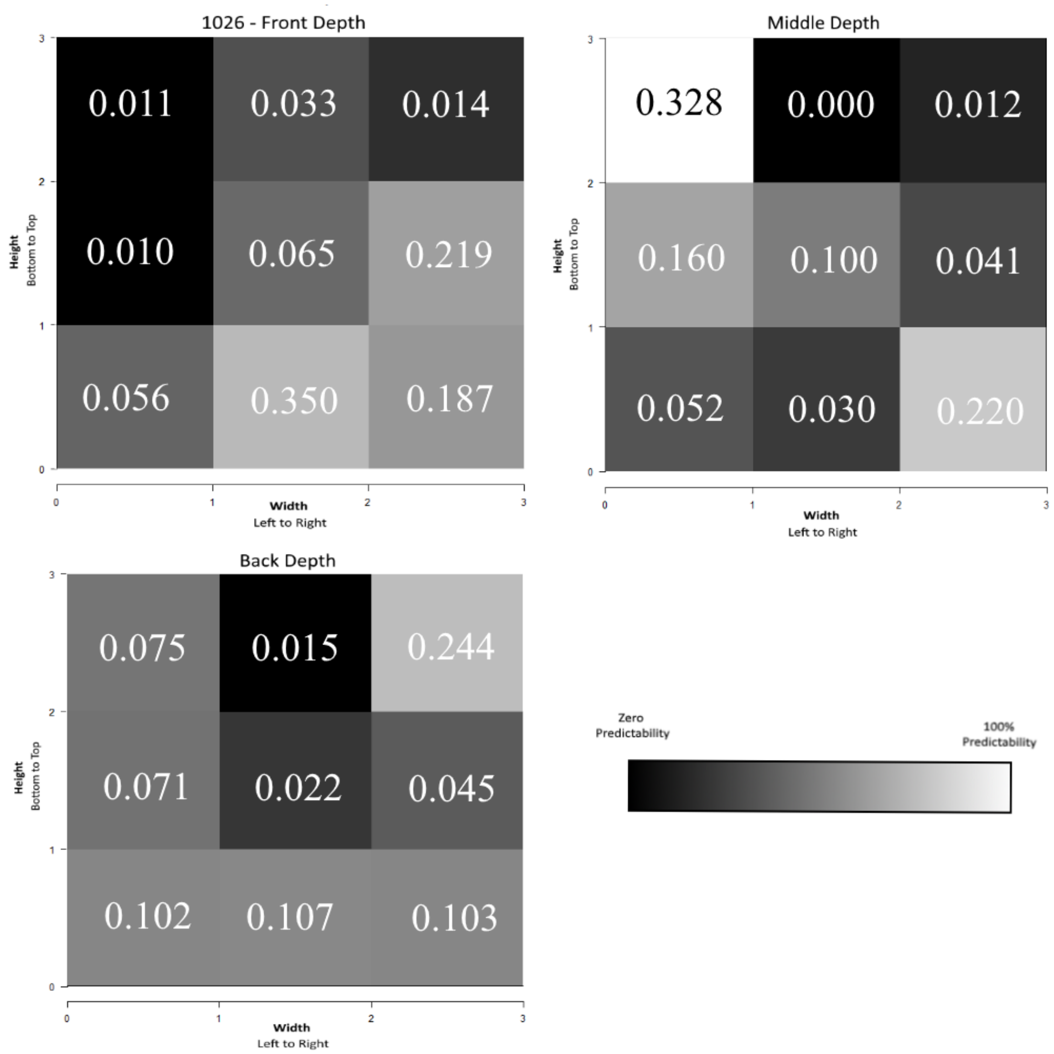



**Figure 5-13: A visualisation of the $R^2$ values of each movement zone for user 1026 (lighter colours show higher $R^2$ value).**

User 1026's movement zones profiles are shown in Table 5-7, where F-RC, F-CB, F-RB M-LT, M-RB and B-RT movement zones showed statistically significant (P-Value) regression models and the high R2 values. F-RC produced a high kurtosis and low standard deviation suggesting that in this zone the user's movements were mainly consistent (with a good fit of the data to the regression model), but occasional overshooting of the target occurred. A high positive skew indicates that a majority of this user’s movement was fast, mean MT was also fast. The F-RC zonal data has a negative gradient of the regression line, suggesting that the user took more time to acquire a target at smaller ID’s. It is possible that the negative regression line gradient may have been impacted by overshooting the target at small ID’s indicated by the high positive kurtosis, or this user simply had more issues perceiving depth at a close distance. Although regression has a statistically significant P-Value and R2 is high, it is not useful to predict movement time for difficulty adaption using this model due to the negative regression line gradient. It may be more useful to look at other statistics to adapt difficulty until the reliability of the model improves. Instead, using kurtosis, standard deviation, skew hits and mean MT may be used to indicate the change in difficulty, whether the challenge needs to be made more or less difficult.

F-RB movement zone produced a high kurtosis, and standard deviation indicates that the user's movement had increased variability in movement time and resulted in a steep regression line gradient indicating that user 1026 took longer to touch target objects at larger ID's. Again, this may have been impacted by the overshooting of the targets. Skew had a high positive value, suggesting the user's movement was frequently fast. The user's movement in F-CB and M-RB zones had a lower standard deviation and a lower positive kurtosis than the F-RB zone; this resulted in a more gradual positive regression line gradient. A lower skew was also found which suggests that movement times were becoming more equally dispersed above and below the regression line. By having fewer overshoots and more movement time spread equally around the regression line, it seems that regression line gradient decreased suggesting that the user movement coordination was more consistent but was not significantly quicker when comparing mean MT (F-RB = 1.087, F-CB = 1.134, M-RB = 0.999). The significance of the models and the other statistical results suggest that the model can be used to adapt to the user's motions. However, the results suggest that the user's movements can still be improved within these zones. Encouraging improvement would be advised by making the challenges easier so the user can train their movement coordination until the zone profile indicates that the user is finding it easier to acquire targets, only after this occurs is it best to challenge the user by increasing the difficulty.

Arguably the best movement performance from user 1026 was seen in zones M-LT and B-RT with a low standard deviation and kurtosis that provides a result that indicates the user was consistent with their movement time. All the zones also provided shallow positive regression line gradient values indicating the user was fast at touching targets. The mean MT found in these zones were the fastest from all zones, suggesting that the user was finding selecting objects in these zones easier. The results are consistent enough for this user to consider difficulty adaptation. In this case, it is possible to consider several options when deciding to adapt. One option is to increase the difficulty to challenge the user, keeping their attention thus helping them to continue playing. Another option is to temporarily remove the user's strong performance zones from user interaction. This directs the user to their weaker movement zones to improve performance and range of movement. The remainder of the zones had a regression model that was less reliable. Therefore they were less suitable for zonal difficulty adaptation. It would be advisable to make the difficulty of these zones easier, to maintain training and improved movement within these zones. User 1026 had several areas that she found particularly weak these where zones M-LC, M-CC, and B-CT. These zones showed weaker regression models and showed both negative kurtosis and a high standard deviation in the regression statistics, suggesting the user movement times were more variable than for other zones. There were also equally as many slow movement times (overshoots) as there were faster movement times. A low positive skew value supports this argument as the low skew indicates that slower movements were occurring in these zones.

# Table 5-7: Analysis of user 1026s movement zones.

| 1026 | Descriptive Statistics | | | Regression | | | | | Performance | |
|---|---|---|---|---|---|---|---|---|---|---|
| Zone | Standard Deviation | Kurtosis | Skew | R2 | P-value | Intercept | Gradient | Sin | Hits (40) | Mean MT |
| **Front** | | | | | | | | | | |
| F-LT | 1.667 | 13.131 | 3.421 | 0.011 | 8.51E-01 | 2.989 | -0.260 | -1.164 | 33 | 1.499 |
| F-CT | 0.467 | 0.123 | 0.921 | 0.033 | 5.99E-01 | 0.965 | -0.196 | 0.705 | 34 | 0.944 |
| F-RT | 0.675 | 3.757 | 2.150 | 0.014 | 8.11E-01 | 1.160 | -0.221 | 0.950 | 33 | 1.042 |
| F-LC | 0.885 | 0.793 | 1.209 | 0.010 | 8.45E-01 | 0.866 | 0.016 | 1.268 | 37 | 1.618 |
| F-CC | 0.534 | 3.368 | 1.964 | 0.065 | 3.92E-01 | -0.476 | 0.107 | 1.781 | 31 | 0.899 |
| F-RC | 0.362 | 6.028 | 2.154 | 0.219 | 1.69E-02 | 0.223 | -0.152 | 1.762 | 36 | 0.836 |
| F-LB | 0.461 | 0.887 | 1.245 | 0.056 | 4.08E-01 | -0.786 | -0.247 | 2.954 | 34 | 1.052 |
| F-CB | 0.504 | 0.490 | 1.016 | 0.350 | 1.58E-03 | -0.661 | 0.131 | 2.659 | 33 | 1.134 |
| F-RB | 0.799 | 9.587 | 2.532 | 0.187 | 4.94E-02 | 0.609 | 1.118 | -3.407 | 32 | 1.087 |
| **Middle** | | | | | | | | | | |
| M-LT | 0.149 | 0.061 | 0.817 | 0.328 | 2.13E-03 | -0.538 | 0.104 | 1.407 | 34 | 0.771 |
| M-CT | 0.480 | 2.158 | 1.639 | 0.000 | 9.99E-01 | 1.025 | -0.013 | 0.030 | 32 | 1.007 |
| M-RT | 0.510 | 2.507 | 1.822 | 0.012 | 8.14E-01 | 2.299 | -0.098 | -1.162 | 38 | 1.009 |
| M-LC | 0.455 | -0.526 | 0.369 | 0.160 | 6.16E-02 | 0.360 | 0.514 | -1.082 | 35 | 1.065 |
| M-CC | 0.447 | -0.519 | 0.879 | 0.100 | 2.43E-01 | 1.221 | 0.231 | -1.966 | 30 | 0.923 |
| M-RC | 0.794 | 1.999 | 1.414 | 0.041 | 5.27E-01 | 0.458 | 0.396 | -0.190 | 34 | 1.251 |
| M-LB | 0.382 | 0.558 | 1.226 | 0.052 | 4.63E-01 | 1.429 | 0.185 | -1.377 | 32 | 0.938 |
| M-CB | 0.250 | 3.428 | 1.869 | 0.030 | 6.03E-01 | 0.385 | 0.027 | 0.507 | 36 | 0.866 |
| M-RB | 0.386 | 7.204 | 2.163 | 0.220 | 2.74E-02 | 1.411 | 0.246 | -2.608 | 32 | 0.999 |
| **Back** | | | | | | | | | | |
| B-LT | 0.548 | 1.739 | 1.293 | 0.075 | 3.36E-01 | 0.925 | 0.500 | -1.261 | 31 | 1.140 |
| B-CT | 0.613 | -0.628 | 0.513 | 0.015 | 7.90E-01 | 1.647 | 0.195 | -0.912 | 34 | 1.500 |
| B-RT | 0.245 | 0.169 | 0.934 | 0.244 | 1.50E-02 | 0.221 | 0.267 | -0.013 | 33 | 0.709 |
| B-LC | 0.606 | 1.825 | 1.288 | 0.071 | 2.96E-01 | -3.699 | -0.152 | 5.922 | 36 | 1.294 |
| B-CC | 0.484 | 0.689 | 1.100 | 0.022 | 6.87E-01 | 1.946 | -0.104 | -0.935 | 36 | 1.152 |
| B-RC | 0.415 | 2.425 | 1.483 | 0.045 | 4.78E-01 | 0.628 | 0.218 | -0.612 | 35 | 0.883 |
| B-LB | 0.331 | 1.077 | 1.204 | 0.102 | 1.78E-01 | -0.067 | 0.297 | 0.411 | 35 | 0.928 |
| B-CB | 1.313 | 12.623 | 3.200 | 0.107 | 1.83E-01 | 1.093 | 0.577 | -4.384 | 33 | 1.205 |
| B-RB | 0.601 | 0.335 | 1.122 | 0.103 | 1.86E-01 | -0.562 | 0.261 | 2.041 | 34 | 1.103 |

### *5.4.1.3.2 USER 1019'S MOVEMENT ZONE ANALYSIS*

Analysis of user 1019's movement zones (Table 5-8) showed that on average the user was faster at depths closest to them and slowest at target location furthest away. At all depths, the user's movement zones show similar results. However, in the middle zones, the mean kurtosis was negative showing that there were as many high movement times as there were lower movement times, and the standard deviation was very similar to all other middle zones. A negative kurtosis shows the user's movement was quite erratic most of the time. A steeper regression line gradient than the front and back zones depths shows that the user was finding the movement task more difficult. Below is a detailed analysis of each movement zone for better analysis of the user's range of movement. Figure 5-14 shows the user's $R^2$ values visual per zone.

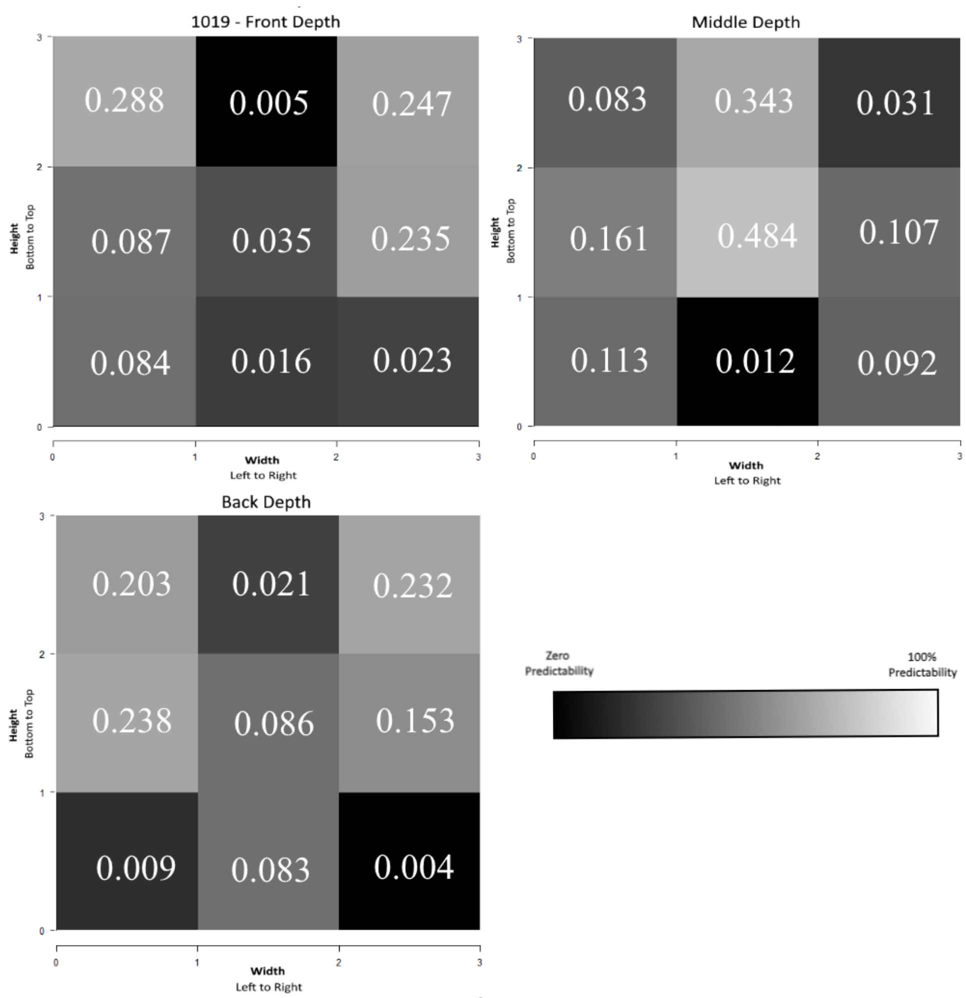



**Figure 5-14: A visualisation of the $R^2$ values of each movement zone for user 1019 (lighter colours show higher $R^2$ value).**

Table 5-8 describes user 1019's movement zone performance profiles. Zone profiles that user 1019 seemed to have suitable regression motion profiles on are F-LT, F-RT, F-RC, M-CT, M-CC, B-LT, B-LC zones. Movement zone profiles M-CT, M-CC, B-LT regression profiles contain relatively high R2 values. However, the other user zone profile values suggest that the user's movement was less accurate – with a negative kurtosis suggesting that there were equally as many overshoots occurring as otherwise, other values suggest that 1019 found it difficult it perform the task in these zones. F-RT and B-LC movement zones profile showed that the user occasionally overshot the target (kurtosis: F-RT=2.782, B-LC=1.812) and the Mean MT was fast (Mean MT: F-RT=1.123, B-LC=1.454) and reasonably consistent (standard deviation) concerning their depth. As seen in user 1026's F-RC zone, with statistics similar to F-RT and B-LC, the gradient of the regression model was negative due to the increasing high overshooting of the targets. 1019's F-RT zone is an example of this. In the case that a regression line gradient becomes negative, it is advised not to use linear regression to adapt difficulty. However, if the regression line gradient remains positive seen in zone B-LC, it is possible to use linear regression for adaptation.

1019 best movement performance was zones F-LT and F-RC, High R2 values explain more of the variability of the movement times. A low standard deviation shows that more movement times appeared nearer to the regression line, the kurtosis produced a low positive value closer to a normal distribution with low skew. This suggests the user had consistent movement times towards the target and would be usable for adaptation to continue challenging the user in this movement area or remove the interaction with this zone to focus on more troublesome movement zones.

Weakest areas for user 1019 was F-CB, M-RT, B-CC, along with having poor regression models, these areas had a high standard deviation, a negative kurtosis, and a low positive skew. Thus, 1019's movement was not consistent as it could be; having a large dispersion of movement time values away from the regression line and that movement time was slower than in other zones. The mean MT tends to show that the user was slower in these areas and seemed to contribute to the user movement performance.

## Table 5-8: Analysis of user 1019s movement zones.

| 1019 | Descriptive Statistics | | | Regression | | | | | Performance | |
|---|---|---|---|---|---|---|---|---|---|---|
| Zone | Standard Deviation | Kurtosis | Skew | $R^2$ | P-Value | Intercept | Gradient | Sin | Hits (40) | Mean MT |
| Front | | | | | | | | | | |
| F-LT | 0.339 | 0.144 | 0.591 | 0.288 | 4.34E-03 | -0.894 | 0.001 | 3.627 | 35 | 1.542 |
| F-CT | 0.367 | -0.333 | 0.799 | 0.005 | 9.19E-01 | 1.551 | 0.069 | -0.465 | 37 | 1.439 |
| F-RT | 0.500 | 2.782 | 1.809 | 0.247 | 9.33E-03 | -0.109 | -0.225 | 2.850 | 36 | 1.123 |
| F-LC | 0.416 | 1.615 | 1.190 | 0.087 | 2.43E-01 | 0.917 | 0.290 | -0.906 | 34 | 1.379 |
| F-CC | 0.441 | 1.706 | 1.000 | 0.035 | 6.32E-01 | 0.860 | 0.134 | 0.670 | 29 | 1.544 |
| F-RC | 0.356 | 0.093 | 0.557 | 0.235 | 2.04E-02 | 0.372 | 0.591 | -0.752 | 32 | 1.305 |
| F-LB | 0.313 | -0.469 | 0.806 | 0.084 | 2.45E-01 | 0.245 | 0.139 | 1.305 | 35 | 1.146 |
| F-CB | 0.685 | -0.576 | 0.802 | 0.016 | 7.76E-01 | 1.228 | -0.174 | 1.306 | 34 | 1.856 |
| F-RB | 0.498 | -0.699 | 0.413 | 0.023 | 7.47E-01 | 0.912 | 0.144 | 0.932 | 28 | 1.916 |
| Middle | | | | | | | | | | |
| M-LT | 0.330 | -0.931 | -0.046 | 0.083 | 2.48E-01 | 0.810 | 0.222 | 0.420 | 35 | 1.499 |
| M-CT | 0.350 | -1.044 | 0.509 | 0.343 | 1.21E-03 | -0.684 | 0.537 | 1.599 | 35 | 1.156 |
| M-RT | 0.611 | -0.312 | 0.529 | 0.031 | 5.91E-01 | 2.707 | -0.323 | 0.417 | 36 | 2.046 |
| M-LC | 0.571 | 0.359 | 0.459 | 0.161 | 5.10E-02 | -1.132 | -0.161 | 5.348 | 37 | 2.255 |
| M-CC | 0.289 | -0.858 | 0.239 | 0.484 | 3.56E-05 | 0.245 | 0.647 | -1.404 | 34 | 1.299 |
| M-RC | 0.483 | 1.200 | 0.866 | 0.107 | 1.82E-01 | 0.852 | 0.483 | -0.825 | 33 | 1.740 |
| M-LB | 0.570 | -0.593 | 0.776 | 0.113 | 2.38E-01 | 2.298 | 0.263 | -3.468 | 27 | 1.638 |
| M-CB | 0.487 | 0.877 | 1.115 | 0.012 | 8.03E-01 | 0.833 | 0.112 | 0.516 | 38 | 1.540 |
| M-RB | 0.339 | -0.123 | 1.053 | 0.092 | 2.15E-01 | -0.377 | 0.113 | 1.634 | 35 | 1.154 |
| Back | | | | | | | | | | |
| B-LT | 0.621 | -0.255 | 0.683 | 0.203 | 2.10E-02 | 0.280 | 0.060 | 4.135 | 37 | 2.482 |
| B-CT | 0.697 | 0.166 | 1.160 | 0.021 | 7.37E-01 | 2.332 | 0.164 | -2.084 | 32 | 1.770 |
| B-RT | 0.577 | 1.117 | 1.272 | 0.232 | 5.47E-02 | -0.361 | 0.430 | 3.021 | 25 | 1.578 |
| B-LC | 0.531 | 1.812 | 1.538 | 0.238 | 1.96E-02 | -2.146 | 0.329 | 3.531 | 32 | 1.454 |
| B-CC | 0.617 | -0.571 | 0.579 | 0.086 | 2.18E-01 | -0.884 | 0.375 | 2.320 | 37 | 2.220 |
| B-RC | 0.322 | -0.674 | 0.630 | 0.153 | 7.58E-02 | 4.821 | -0.266 | -2.973 | 34 | 1.616 |
| B-LB | 0.594 | 5.139 | 2.163 | 0.009 | 8.56E-01 | 0.860 | 0.097 | 0.195 | 36 | 1.155 |
| B-CB | 0.244 | 0.202 | 0.687 | 0.083 | 2.72E-01 | -0.117 | 0.131 | 1.388 | 33 | 1.423 |
| B-RB | 0.544 | 0.936 | 1.203 | 0.004 | 9.98E-01 | 1.585 | -0.004 | 0.142 | 33 | 1.665 |

## 5.4.2 USABILITY

It is important that a VR upper limb rehabilitation system should require a minimal amount of learning to perform tasks efficiently. The design should exclude problems that may cause improper actions or blocks the user from interacting. The design should provide a pleasant experience and have high memorability to ensure users remember how to use the systems with minimal relearning when they return. To assess the usability of TAGER, semi-structured interview with questions (APPENDIX E) that invite the participant to discuss their experience using the TAGER were conducted. Questions related to the VR headset, fatigue, and overall performance. In general, only 19% of participants found their experience to be frustrating at times, where the main frustration expressed was due to a persistent message that appeared on screen when the tracking stopped due to the technology disconnecting. This may become an increasing problem over continuous use and will need further design consideration in future. 27% of the participants mentioned that they became fatigued at points during the experiments.

### 5.4.2.1 VR HEADSET

77% of the participants commented that their experience using the VR headset was enjoyable, 43% of participants mentioned that they perceived their performance to have improved while wearing the VR headset. Furthermore, 19% of the participants said they needed time to adjust to wearing the headset and the view within the headset. A critical issue for the successful implementation of VR headsets in VEs is the minimisation of the motion sickness; none of the participants in this study mentioned that they suffered any motion sickness when using the VR headset. Comparing user performance between the VR headset and monitor only, with cues and without cues, a paired t-test was used to determine significant differences between users average MT, it was found that there was no significant difference in Cues ($T=1.681$; $DOF=21$; $p=0.053$) or No Cues ($T=1.591$; $DOF=21$; $p=0.063$), though there was a consistently slower user response when using the headset (Table 5-9). There are several potential reasons why users were slower with the VR headset, including but not limited to the lack of familiarisation of the technology among participants, the change of viewing perspective, possible reduce awareness of surrounding or not seeing the Leap Motion Controller while the headset is worn.

Wearing the VR headset did seem to decrease the mean amount of successful hits, suggesting that users had less accurate movements to record higher successful hits. However, it found no significant differences in the decrease of the successful hits, with or without cues. Table 7 compares regression results, modelling the users' movement through Murata's multiple regression showed that the VR headset explains more of the variability of the response data, producing higher R-Squared values for both cues and no cues. VR produced a steeper regression line gradient from the linear regression model for cues and no cues; this indicates that at a fixed ID the predicted movement time for users would be higher. Using the VR headset, linear regression suggests users needed more time to select a target object; this corresponds with the higher mean movement times seen using the VR headset. Regression suggests that users' organisation of movement in the VE had improved movement performance with VR. The improved performance seemed to agree with the participant's subjective experience on their movement performance obtained from the questionnaires, even though users tended to be slower in VR. However, this is not a significant issue so long as the effect is consistent among users, and it is a consideration for future interaction design.

**Table 5-9: Comparing the VR headset against the PC monitor: Cues (C), No cues (NC).**

| | **VR (NC)** | **Monitor (NC)** | **VR (C)** | **Monitor (C)** |
|---|---|---|---|---|
| Gradient | 0.552 | 0.436 | 0.670 | 0.504 |
| Intercept | 0.097 | 0.236 | -0.108 | 0.138 |
| R-Squared | 0.138 | 0.123 | 0.158 | 0.129 |
| Mean MT (ms) | 1174.2 | 1107.4 | 1165.0 | 1115.4 |
| T-test P = (0.05) | 0.063 | | 0.053 | |
| Mean Hits (108) | 81 | 85 | 85 | 87 |
| T-test P = (0.05) | 0.08 | | 0.24 | |

### 5.4.2.2 CUES AND SPATIAL AWARENESS

Feedback cues are provided on target proximity and acquisition through lighting and shading, as well as vibration from the Myo armband for notification of immediate target acquisition. Figure 5-15 shows the variation of interaction difficulty with cues and without cues for different sized objects (large – LRG, medium – MED and small – SML). The results show that on average cues increased the number of successful hits and users became faster at reaching target objects, while generally these results as expected, it is not clear that cues improve performance for MED cue acquisition and more investigation is required. Participants' subjective opinion on the impact that cues had on their performance was at odds with the quantitative results found, 83% of participants did not notice any impact on performance when cues were introduced. Further assessment of cues versus no cues from the regression analysis seen in Table 5-10 which shows the results of the mean regression line across all users for cues and no cues. Using cues provides a more gradual regression line gradient revealing that cues supported users to improve their movement performance. All users produced a mean $R^2$ value higher when cues where introduced (NC = 0.126, C = 0.133), providing a model that is more predictive of movement time.

**Table 5-10: Comparing the performance of cues (C) and no cues (NC) across all users.**

| | No Cues (NC) | Cues (C) |
|---|---|---|
| Intercept | 0.217 | 0.104 |
| Gradient | 0.488 | 0.466 |
| R-Squared | 0.126 | 0.133 |

It was found that targets positioned at the centre depth (relative to the user) were more successfully acquired – a mean of 29 per task overall participants (Front = 22, Back = 26). Closer objects appear to have been harder to attain, suggesting the need to consider moving the minimum distance further away (along the z-axis) or move objects closer to the z-axis along the x and y-axes. The latter suggests a cone area (Cha and Rohae, 2013) for object placement – with the cone pointing towards the user – rather than a cuboid (which maps well to the Leap Motion Controller's detection area). This might account better for arm kinematic differences in attaining targets in close and far locations. Users attained targets in all areas with reasonable success, though on average there were 31 (28%) unsuccessful acquisitions per level from a total of 108 targets. This may be considered quite high for able-bodied users, if the Leap Motion is mounted on the VR headset, pointing forward (users facing direction) it could provide a more natural interactive space, and reduce unsuccessful acquisitions.

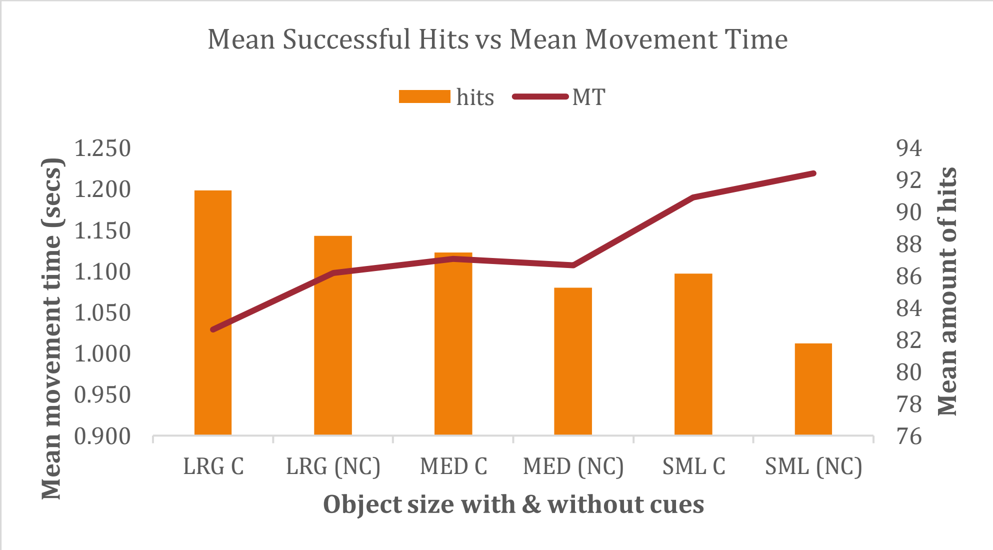



**Figure 5-15: Variation of interaction difficulty arranged by the mean magnitude of the target object for all participants.**

# 5.5 DISCUSSION

In this study, participants used TAGER, a 3D VR reaching exercise system. Evaluation of TAGER was conducted using able-bodied participants to improve the design and usability of the system before using in a later experiment with upper limb impaired participants. Another reason for this study was to investigate the suitability of Fitts Law and variants for modelling user movement within a 3D natural user interface using the Leap Motion Controller. Assessment of Fitts Law and its variants across all participants, it was discovered that on average each of the Fitts law equations produced similar patterns of results in the regression line gradient coefficients and y-intercepts. However, results from the multiple regression approach of Fitts Law showed greater values in $R^2$ at the start and end of the experiment when compared to others; this shows that the multiple regression approach explained more of the user's movements thus an increase in the predictive quality of the model. From the result, it was decided that multiple regression Fitts law would be used to continue with the analysis of the participant's user movement profiles.

Analysis of the individual user movement profiles for each participant over-time shows that some participants, despite having a 10-minute training stage to become familiar with TAGER they produced weak user profiles at the start of the experiment and produced a strong user profile at the end that was indicative of the participant still in a learning phase. Some participant recorded a user profile that was stronger than at the end of the experiment showing those users may have experienced fatigue in their movements. It was possible to identify participants that adopt different movement behaviours; one user seems to adopt a high-risk strategy shown by their faster movement times and lower target acquisition performance along with regression and descriptive statistics that indicated increased variable in user movement showing a poorer user movement profile at the end of the experiment. Another participant had a different approach by slowing down their target acquisition improved, regression results improved increasing the predictability of the participant, and descriptive statistics supported the improvements in movement coordination. In the experiment, it was possible to produce user movement profile in each of the movement zones the participants had to reach and touch a target. Analysis of two participants showed that it was possible to identify weaknesses and strengths in participants’ range of motion. It is possible that when this information is reviewed by clinicians that it could help focus on targeting areas of movement weakness for conventional rehabilitation. For a VR rehabilitation system, this could be useful for feedback to the user information about the strengths and weakness in their movement to motivate them to improve their performance in weak movement zones. This information could also be useful to adapt the difficulty in each movement zone, adapting per movement zones provides a more personalised user experience. Identifying areas of movement weakness from the movement zone profile and adapting the task to make it easier enables the patient to continue training to improve rather than forcing the patient to continue movement tasks within a zone that is too challenging, which could cause frustration in the patient.

Participants expressed a largely positive view of the usability of TAGER; some participants did state that they became occasionally frustrated with the persistent negative feedback displayed on the screen when the Leap Motion Controller lost tracking of the user's hand. When participants wore the VR headset, most of the participants found the experience enjoyable and nearly half of the users said that they perceived their performance to have improved while the VR headset was worn. However, some participants did mention that it took time to adjust to wearing the VR headset and the viewing experience within the headset, future systems may have to account for this. No participants experienced any level of motion sickness during the wearing of the headset; this is encouraging ahead of experiments with stroke patients as stroke patient may be more susceptible to motion sickness due to their potential vision problems. Comparing the VR headset against the PC monitor only, it was found that participants were slower using the VR headset and target acquisitions reduced with and without cues. However, the results were not significantly different. With the VR headset, the regression statistics improved in predictability having higher $R^2$ values with or without cues than the PC monitor. Regression line gradient coefficients were steeper that supports the slower movements seen by the VR headset. However, this is not a significant issue so long as the results are consistent among users. The adding and removing of visual, and tactile cues were analysed, among all users, the introduction of cues increased improved target acquisitions and user became faster than with no cues. This was at odds with most user's subjective opinion; they did not notice any changes in cues. Regression statistics comparing cues and no cues showed users were becoming faster with cues and increasing in predictability. Target objects closer to the user were more difficult for participants to acquire, it would be suggested to move closer objects further from the user or move objects closer along the x and y-axis suggesting a cone-like shape. If the Leap Motion Controller was head mounted, facing the user's forward orientation, it could improve the natural interaction space and improve target acquisition.

Before the study with upper limb impaired participants, improvements to TAGER are required to improve the quality of the reaching and touching rehabilitation exercises. Modification to the hand tracking space are required to reduce the failures in hand tracking and reducing the negative feedback experienced by the participants. thus, reducing the level of frustration experienced by the users. Additional statistics to the user’s movement profile should be added to explain the users’ movement variations better, to help increase the accuracy of the user profile for modelling movement performance.

## 5.6 CONCLUSION

A VR rehabilitation system for reaching and touching exercises was developed called TAGER; it was tested with able-bodied users to investigate Fitts Law as a tool for modelling user movement using novel natural user interfacing devices toward the design of an adaptive interface. Evidence shows that it was possible to profile user movements using Fitts Law in a 3D environment while using the Leap Motion Controller as a markerless hand tracking input device. The user profile identified learning effects, fatigue factors and specific movement behaviours produced by participants. The system had a favourable opinion on usability by participants. Future systems should consider improvements to hand tracking to reduce frustration to provide a more enjoyable user experience.

# 6 EVALUATING TAGER WITH UPPER LIMB IMPAIRED PARTICIPANTS

## 6.1 CHAPTER OVERVIEW

This chapter outlines the evaluation of TAGER as a rehabilitation tool for reaching and touching exercises with upper limb impaired participants. Evaluation of TAGER's capability to model the movement performance of upper limb impaired participants using the movement profiler developed in the previous experiment. Results are compared against able-bodied participants to examine the diversity of movement performance.

## 6.2 AIM AND OBJECTIVES

The overall aim of this experiment was to evaluate TAGER with upper limb impaired users following a stroke and to compare the results against those of the abled bodied participants.

This experiment had two main objectives:

1. Investigate the usability, acceptability, and technical performance of the second prototype of TAGER to provide reaching and touching rehabilitation exercises.
2. Investigate the suitability of Fitts law for modelling impaired user movement in reach and touch tasks in a natural user interface while using a VR headset mounted Leap Motion Controller to track hand movement.

Experimental data was obtained quantitatively via recorded tracked user data within TAGER, and Qualitative data was obtained from questionnaires and semi-structured interviews.

# 6.3 DESIGNING FOR UPPER LIMB IMPAIRED USERS

Before the study with upper limb impaired users, several visits were scheduled to clinicians at local hospitals, clinics and PPI sessions at the Northern Ireland Chest Heart and Stroke Association (NICHSA) charity, to demonstrate the TAGER system with clinicians and stroke patients to receive feedback. These feedback sessions gave insight into several important changes (APPENDIX T) that would be necessary to enable the clinic's service users to engage in the experiment and interact with TAGER, Table 6-1 shows a list of additional requirements gathered and modifications needed for the system to be more suitable for upper limb impaired participants, section 6.3.1 describes in more detail the rehabilitation specific changes required. One of the clinics, Brain Injury Matters clinic, permitted recruitment from their service users and used their facilities to conduct the study. Below discusses clinical feedback that impacted TAGER's design for this study. However, the TAGER's underlying design concept and the main experimental aim remain as in the previous abled bodied experiment so that the results that can be more easily compared.

**Table 6-1: A list of additional requirements gathered from PPI sessions, hospitals and clinic visits.**

| Requirement Description | Type |
|---|---|
| Calibration of the user's arm reach is necessary to adjust/personalise the virtual space for each user so they can easily target objects | Rehab Specific |
| Time limit on target appearance, the target should only appear for a certain time and be able to move to the next target in case users can't select the current target, possibly due to fatigue or range of movement limitations. | Rehab Specific |
| From the previous study, the difficulty in targeting objects closest to the user may be a result of the orientation and position of the leap motion. It might be better if the Leap motion was mounted on the user's head. | Hardware Specific |

| | |
|---|---|
| From previous study users were found to be overshooting. Change the system to track data to determine if overshooting does happen and how often it happens | Game Specific |
| Ensure minimal cybersickness within the system as stroke patients will have increased chances of cybersickness. | Game Specific |

### 6.3.1 SYSTEM CHANGES FROM CLINICAL FEEDBACK

#### 6.3.1.1 ARM CALIBRATION

In the previous experiment, object placement in TAGER was predefined by the extent of Leap Motion's tracking space, based on the Leap being placed on the table, rather than by considering a person's range of movement. Clinicians at the Brain Injury Matters clinic and Altnagelvin Area hospital thought that this could be an issue and suggested that TAGER should account for the user's capability in the placement of objects, causing the users to become frustrated, tired and may overexert themselves if they are trying hard to select a target object. This would not be ideal for rehabilitation purposes and could result in users learning incorrect movements in the long-term. They advised that it would be useful to measure how far the users could reach into the virtual scene. By measuring the user arm reach at the beginning of the session, the target objects could then be adjusted positionally to be placed inside the users' reaching space. The new calibration process would then begin by asking the user to extend their arm as far as possible without leaning forward to touch and aim for a marker placed inside the virtual world. When a timer ends the users' reaching length was determined by how far the virtual hand was away from the user's head. This measure was then used to calculate each target object position before it appeared on the screen.

#### 6.3.1.2 TIMEOUTS

After the study using TAGER with able-bodied participants, the feedback was gathered from a visit to Brain Injury Matters clinic ahead of experiments with upper limb impaired participants. The clinicians thought that even if the objects are placed in the person's reaching space from the calibration, it may also be possible that users may not be capable of reaching into a particular area. This could be due to their health condition, particularly fatigue while using TAGER. In the original design of TAGER, users had to select the target object before the next target object could appear. To resolve this issue, it was decided to design TAGER to include a timeout on objects that the users could not reach. When a target object appeared a timer of 10 seconds would countdown in the background, after 10 seconds the object would be removed from the user's view, and the next object would appear. The number of timeouts occurring throughout the session was counted to determine if this provided an insight into the user movement performance.

#### 6.3.1.3 OVERSHOOTING

The study with able-bodied users using TAGER found that in some cases users had high variability in their reaching and touching movements. The user overshooting of the target most likely caused this variability. Overshooting is when the user has moved toward the target but has misjudged where it is in virtual space; often moving beyond the object and having to come back and attempt to select the objects again. It was thought that it would be useful to investigate the occurrence of overshoots and the impact that might have on user motion profiles. TAGER was altered to continuously track the user's hand as they reached for a target object and if the user's hand position has a z-axis depth value greater than the target object position this was classified as an overshoot. All the overshoots were counted and stored for further analysis.

#### 6.3.1.4 LEAP MOTION CONTROLLER ORIENTATION AND POSITION

It was realised from results in the able-bodied user study, that users found the object positioned at the front more difficult to select than expected. This seemed to be at odds with the theory of Fitts Law; that objects closer and larger should be faster to hit but may have been in part due to the position of the Leap Motion Controller on the desk. The Leap Motion Controller’s hand tracking area is generally in a cone-like shape getting narrower the closer the hand gets to the infrared camera seen in Figure 6-1. It was considered a good idea to place the Leap Motion Controller on the user’s head facing the user’s forward-facing direction (Figure 6-2). In the previous study, it was not possible to do this due to the beta SDK version of the Oculus DK1 being incompatible with the head mounted Leap Motion Controller capabilities. However, before starting the next experiment Oculus released their commercial VR headset which made it possible to head-mount the Leap Motion Controller. This seems a more natural fit as the Leap Motion Controller's tracking space now corresponded well to the user viewing space. Hand tracking with the head mounted Leap Motion Controller becomes more natural, and interaction could be improved helping to confine the user's movements within the Leap Motion Controller's tracking space. Possibly helping to decrease the user's hand getting lost. Furthermore, with the changes in tracking orientation, it was necessary to adjust the object's position in the VE, from the cube-like shape to a cone shape to replicate the tracking space of the Leap Motion Controller (Figure 6-1), the objects where placed in this cone-like shape in the users fixed forward-facing view. This means that if a user moved their head, the objects remained in the same location. The user's head was free to move in 6DoF, to help users focus on the target object to ensure hand-eye coordination was possible.

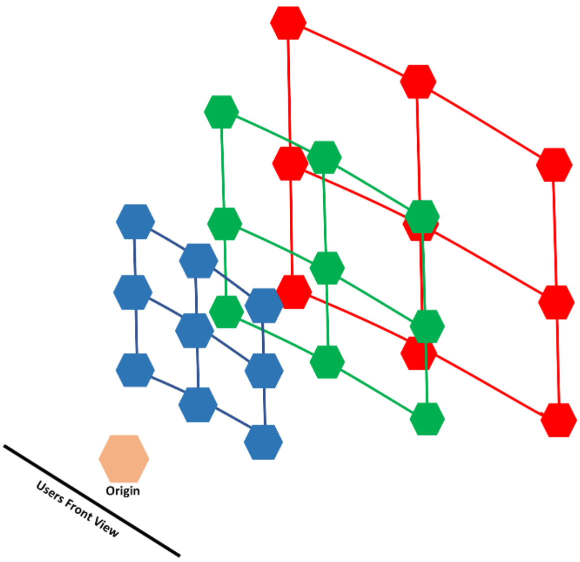



**Figure 6-1: TAGER's fixed object placement, shaped in a cone-like shape to match the Leap Motions Controller's tracking space shape.**

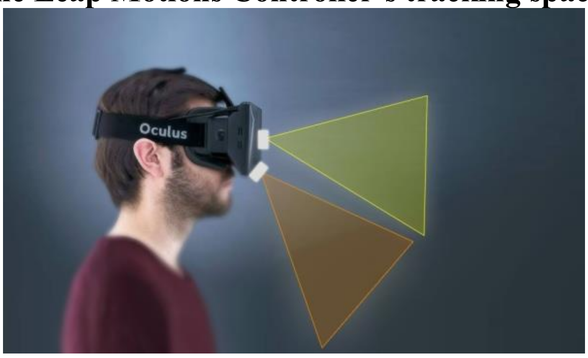



**Figure 6-2: The Leap Motion's tracking orientation when head-mounted.**

The design of the study requires switching between two viewing mediums; through a VR headset worn on the user's head and on a PC monitor. With the VR headset is worn the Leap Motion Controller is fixed to the front of the headset. However, this is not possible when using the PC monitor, so it was decided that a custom 3D-printed Leap Motion mount be designed and attached to a head strap, to enable the use of the leap motion in a head-mounted position when using the PC monitor. The custom Leap Motion head mount was built with a hinge to adjust the angle of the tracking space to improve tracking for users who have more severe upper limb impairment (Figure 6-4). Figure 6-3 shows both methods for fixing the Leap Motion Controller to the user’s head when using the VR headset and the PC Monitor only.

A B

**Figure 6-3: The two types of Leap Motion Controller head mounts and the direction of its tracking space (A: No VR head mount, B: VR headset mounted)**

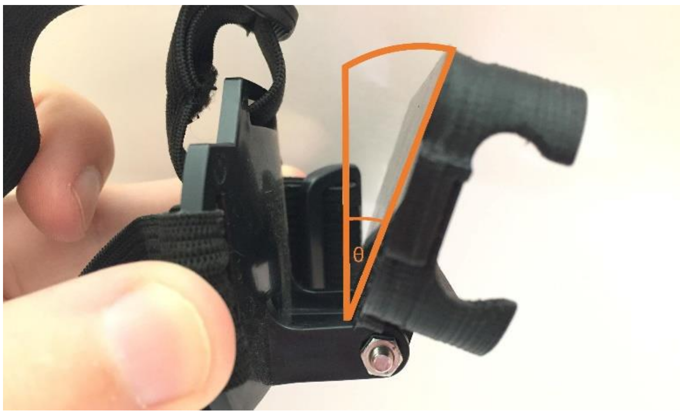



**Figure 6-4: Leap Motion Controller head mounted strap with hinge for adjusting the camera angle**

# 6.4 METHOD

## 6.4.1 EXPERIMENT DESIGN

This experiment had a single use structural design and was approved by the OREC research ethics committee (REC Reference 16/NI/0112). The study was conducted at Brain Injury Matters, a charity rehabilitation centre in Belfast, UK. The equipment was set up and experiment conducted in a private physiotherapy room, where the participant normally performed physiotherapy with a physiotherapist. The room and equipment setup was the same for every participant to prevent any variabilities in the experimental procedure.

## 6.4.2 PARTICIPANTS

Participants who had suffered from upper limb impairment due to a stroke or traumatic brain injury were recruited. Participant eligibility for this study is summarised in Table 6-2. Adults aged 18 or over were recruited, who had enough motor capacity and strength to lift their arm from a desk and could follow a two-step command. Participants were excluded if they had:

- Severe upper limb dysfunction indicated by a score of less than 25/100 on the upper limb motricity index (Crosbie *et al.*, 2012).
- A mini-mental test score of less than 7/10 indicating cognitive difficulties (Hodkinson, 1972).
- The star cancellation test should not be less than 48/52 (Crosbie *et al.*, 2012). This assesses the level of spatial neglect in the near extrapersonal space (reaching space).
- Arm pain greater than 6/10 on the visual analogue scale (Crosbie *et al.*, 2012).
- Diagnosed vision problems that can't be corrected by wearing spectacles such as blurred vision, double vision, light sensitivity, colour distortion or depth perceptions issues.
- Learning difficulties or health issues that are not a result of upper limb impairment.

The lead physiotherapist at Brain Injury Matters determined eligibility and conducted the required assessments at least a week before users could participate. A short questionnaire covering the general inclusion and exclusion criteria was also given to each potential participant, which was filled in with the assistance of the physiotherapist (APPENDIX G). A short information sheet was also given to the potential participants by the physiotherapist, which was also read aloud by the investigator on the day of the experiment to ensure the participant understood what they were doing and why. Once the potential participant agreed to take part, a consent was signed by the participant on the day of the experiment.

**Table 6-2: Eligibility criteria for the study**

| Inclusion | Exclusion |
|---|---|
| Ex1. Individuals at any stage of either stroke or traumatic brain injury with mobility problems of the upper limb. | Ex2. Severe upper limb dysfunction as indicated by a score of less than 25/100 on the upper limb Motricity index. |
| Ex3. Ability to lift their hand from a desk. | Ex4. Cognitive difficulties indicated by a mini-mental score test of less than 7/10. |
| Ex5. Able to follow a two-step command. | Ex6. Perceptual difficulties as indicated by star cancellation test less than 48/52. |
| Ex7. Aged 18 years or older. | Ex8. People diagnosed with vision problems that can’t be corrected by the wearing of glasses such as colour blindness and light sensitivity. |
| | Ex9. Comorbid conditions affecting their rehabilitation potential. |
| | Ex10. Arm pain greater than 6 out of 10 on a visual analogue scale. |
| | Ex11. Adults with separate learning or health issues that are not a result of their upper limb impairment. |

### 6.4.3 HARDWARE AND SOFTWARE

The technology used for this study was similar to that used in the previous study, to facilitate comparison with able-bodied users. The software was designed and developed using the Unity game engine 5.6 and was run on a DELL, 64-bit Windows 8.1 laptop with Intel Core i5@2.5Ghz, 8GB RAM and 500GB hard drive. A Microsoft Kinect 2 is mounted on top of a video camera stand next to the PC monitor to record upper body motion. A Myo armband was worn by the participant to monitor EMG reading from the forearm during motion and also used for tactile feedback. The main interactive device used was the Leap Motion Controller to interact with the VE and was attached to the participant's head or on the VR headset seen in Figure 6-3. The newest Oculus CV1 VR headset was used and worn at intervals, and a 22" PC monitor at (1920x1080) resolution was used for the remainder of the time as the viewing mediums. Figure 6-5 shows the layout of the technology used.

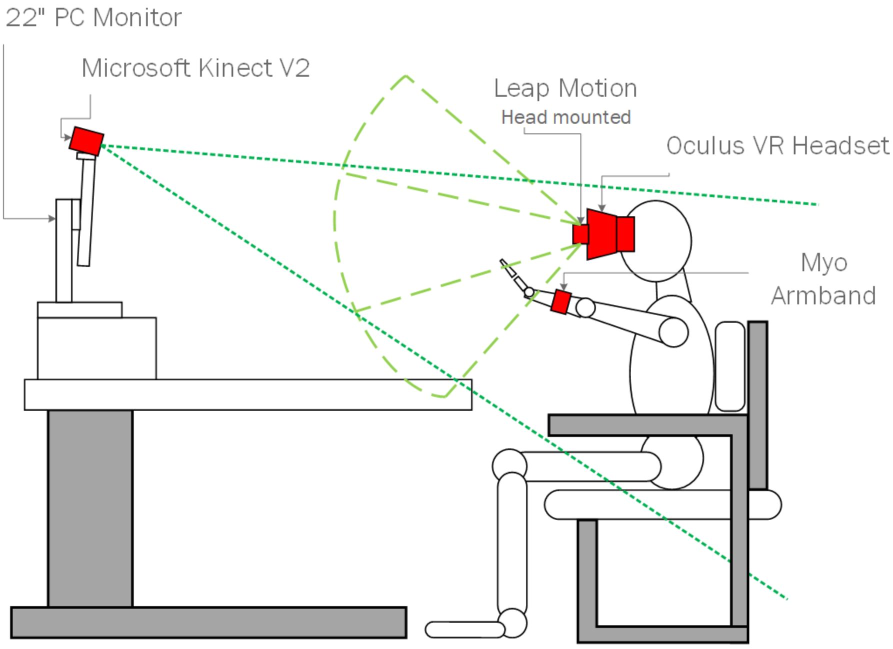



**Figure 6-5: TAGER's new experiment setup with the Leap Motion Controller head-mounted**

### 6.4.4 EXPERIMENT SETUP

The experiment process comprised of four stages:

1. *Demonstration* – After the user has consented to take part in the study, the participant observes the investigator performing the actions while using the TAGER system. The investigator demonstrates how the calibration is achieved and how the movement tasks are performed. During observation, the investigator invites the participant to ask any questions to answer any concerns or to explain their involvement in the study more fully. The investigator instructs the user that at certain times during the experiment they will have to switch headgear from the custom leap motion strap to the VR headset and vice versa. Placement of the headset on the participant's head will be aided by the investigator. After a demonstration, the investigator advises the participant that their health and safety is important and if they feel uncomfortable or in pain, they should express this to the investigator so that prevention measures can be taken, the participant can stop at any time during the experiment if they feel they cannot continue.
2. *Training* - next the participants go through a practice stage where they use TAGER for a ten-minute period that is observed and guided by the investigator. The training stage aimed to give the participant an opportunity to learning the new interface technologies, particularly the Leap Motion controller, as it was unlikely that the participants would have previously used such technologies. Training also gave the participant the chance to practise the interaction they previously observed in the demonstration to become more familiar with what movements were expected of them. The investigator and clinician also had the chance to observe the participant's actions and the severity of their condition to decide whether it would be safe for the participant to take part and that they were capable of interacting without injuring themselves or making their condition worse.
3. *Official TAGER* – when training finishes each participant is given a two-minute rest period to alleviate any tiredness before starting the complete official TAGER experiment. The participants will experience ten levels:
    a. The first and last levels (1 and 10) are identical in the attributes they possess. This was purposely designed to investigate each

participant’s performance over the course of the experiment. This may give insight into the participant’s level of fatigue, the rate of learning or movement behaviours adopted.

b. The remaining eights levels (2-9) were designed to have distinct scene attributes such as multi-model cues, target object size, and the type of viewing medium. These levels are given to the participants to investigate their impact on their movement performance (Figure 6-6). Levels 2-9 are also randomised per individual to eliminate any bias in the ordering. At the end of each level, the participant is given a 30 second rest period and a further ten secs between each repetition to reduce tiredness between each level. The scene attributes used in the experiment include:

    i. *Visual Cues* – shadowing and proximity colour change was incorporated into TAGER. Lighting for the VE was carefully set up to provide high-quality shadows that cast obvious shadows of the user’s hand and the target object onto the floor of the VR room. It was expected that shadows would help participants judge the depth and position of their hand relative to the target object.

    ii. *Tactile cues* - are given to the user through the Myo armband worn on the forearm of the participant. A small vibration is felt on the participant’s skin immediately as soon as they successfully touch a target object. Thus, providing the user with immediate haptic feedback on target acquisition.

    iii. *Target Scale* - was changed between three different sizes (Small = 2cm, Medium = 3.5cm, Large = 5cm). To investigate if cues are more important for smaller object acquisition. Though it is noted that larger objects provide more significant visual cues (e.g. shadows are larger. Cues may improve accuracy and increase user arm kinematics speed.

    iv. *Viewing medium* – may also influence user movement performance. TAGER uses both a PC monitor and the

Oculus CV1 as the viewing modes for comparison. To investigate the effects of these scene attributes and gain knowledge on their impact on arm kinematics, spatial awareness, movement speed and accuracy.

4. *Discussion* – at the end of the experiment the investigator leads a semi-structured interview with each participant to receive feedback on usability, enjoyment and acceptability of the technology. The investigator guides the participant through two post questionnaires to obtain further feedback. The first questionnaire asks the participant questions relating to the specific experience when using TAGER. For example, their feelings on movement performance and their thoughts on the VR Headset. The second questionnaire used the established System Usability Scale (SUS) to assess the general usability of TAGER. Based on research on usability a score greater than 68/100 for a product is considered to have above average usability. When delivering the questionnaires, the investigator read out the questions and filled in the participant's responses to minimise the effort of the participant as they may not be able to read/understand the questions and may be unable to write a response due to their condition.

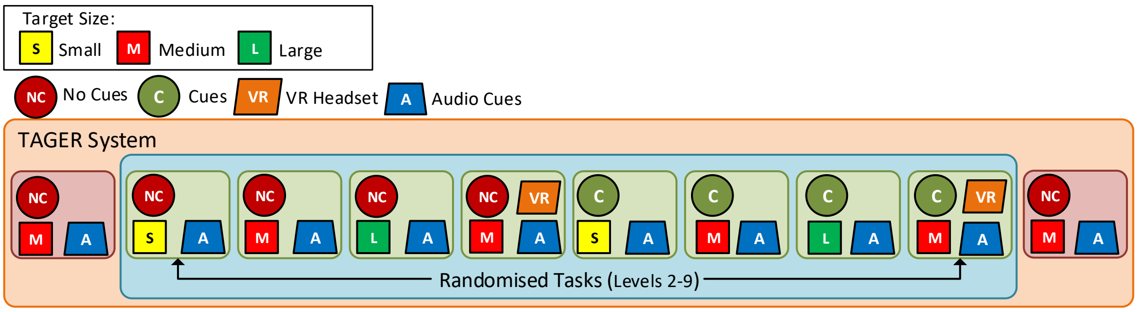



**Figure 6-6: Nine different stages of the experiment. The diagram above shows the different scenarios that a participant experienced in each stage when performing the interactions in TAGER.**

# 6.5 RESULTS

Participants (n=8) were recruited for the study, comprising of six females and two males. Three out of the eight participant's data were not analysed due to these participants not being able to complete the experiment as they were not able to maintain concentration or became too tired over the length of the experiment. The average age of the participants was 51 years old, the average time since their injury was 12 years, most participants did have severe upper limb motor weakness, and for most, it had been a long time since they received regular rehabilitation for their upper limbs. Participants' use of the system on average took 103minutes (1hr 43mins). For each participant, a physiotherapist was present during the entire length of the experiment. Table 6-3 describes each participant's upper limb characteristics, game and computer use characteristics. User data was recorded as they performed object reaching and touch tasks from an origin to a target for various distance and object sizes.

**Table 6-3: Participant disability, demographic, game and computer use characteristics**

| User | Age | Gender | Time since injury | Paretic arm | Dominant arm | Game genres played | Time playing games | NUI | PC hrs. | Pointing device |
|---|---|---|---|---|---|---|---|---|---|---|
| 2001 | 62 | F | 2.7 | L | L | Puzzle, Board, Casual | Once a day | N | 15 to 40 | TrackPad |
| 2002 | 55 | F | 5 | R | R | Puzzle, Casual, Handheld | Once a day | N | >40 | Mouse |
| 2003 | 55 | F | 9 | L | L | Puzzle, Handheld | Once a day | Y | <1 | Mouse |
| 2004 | 45 | M | 7 | L | R | Puzzle, Board | Rarely | N | <1 | Mouse |
| 2005 | 38 | M | 13 | R | R | Console & PC | Once a day | Y | 1 to 5 | TrackPad |
| 2006 | 54 | F | 15 | L | R | None | Never | N | <1 | Mouse |
| 2007 | 56 | F | 9 | L | R | Puzzle, Casual, Handheld, Console & PC | Once a day | N | >40 | Touch |
| 2008 | 40 | F | 36 | R | L | Casual, Handheld | Rarely | N | 15 to 40 | Touch |

It was clear that after two participants took part in the experiment, they were struggling to complete the experiment or taking too long to finish the experiment. Although these first two participants did complete the experiment, it was thought it would best to reduce the length of time due to concern about future participant fatigue, and to ensure this factor did not affect recruitment opportunities and thus maintain participant completion rate. TAGER's scene attributes and levels were altered as below

a. The number of levels reduced from ten to six, removing all levels that excluded cues from the scene attributes. From the previous study, the results showed that cues improved target acquisition and it was more important to use TAGER to evaluate the Fitts Law model than evaluate the use of cues.
b. The number of repetitions was also reduced from four to three meaning the user only had to acquire 81 targets instead of 108 per level. 81 targets would still give enough data points for Fitts Law analysis per level while also giving the participant fewer targets to hit.

As a consequence of these changes, it was not possible to analyse the impact of cues on participant movement performance in this experiment. It was also not possible to perform a comparative analysis of each of the participant's movement zones (section 5.4.1.3) with able-bodied participants as the number of data points per zone were significantly reduced. However, more importantly, it was still possible to compare user movement profile changes over time. It was also possible to investigate differences between the VR headset being worn against no VR headsets and compare to able-bodied participant results. Figure 6-7 shows the new structure of TAGER's scenes and levels.

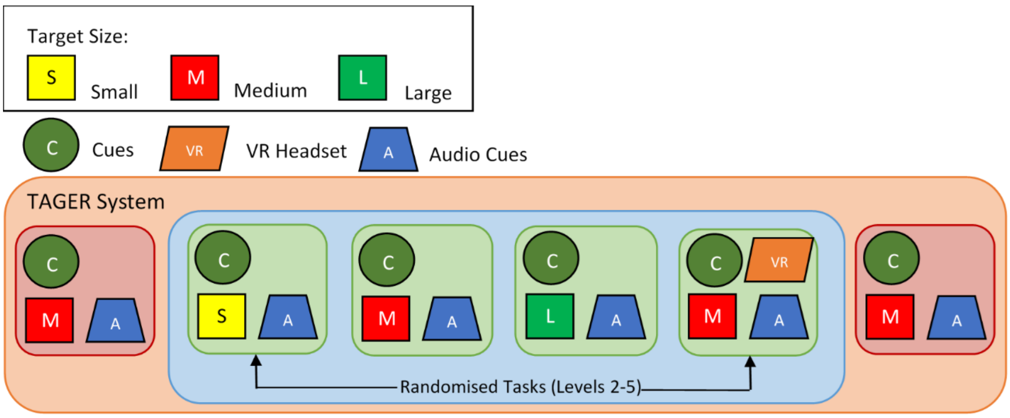



**Figure 6-7: The newly modified level structure of TAGER experienced by upper limb impaired participants.**

## 6.5.1 USER PROFILING

The nature of this experiment was fundamentally exploratory; to investigate the creation of a user movement model that could help understand how best to create an adaptive VR system that can personalise interactive tasks for upper limb impaired individuals. It is possible to use user movement profiles developed to gain tangible insights into user movement capabilities, and dynamically alter task difficulty by changing parameters of the interactable objects, such as distance from the user, the scale of the object, and the direction from the user. As explained in the experimental setup, the experimental design specifies the use of two identical TAGER levels; one placed at the beginning of the experiment and the other place at the end of the experiment. This facilitates the investigation of learning effects indicated by improved performance or identifying potential fatigue effects resulting in performance decline.

With the low number of participants recruited for this study, it would be better to investigate each user profile in-depth and focus more on understanding core trends and variations between people. Each user's profile contains statistics consisting of regression parameters that explain the relationship between the user's movement times and the difficulty of the task (ID). These statistics also explain the regression line fitness for prediction of future movement times by the user. The profile includes descriptive statistics calculated using the residuals of the linear regression; they describe the variation of the user's movement times along the regression line. Finally, other target performance statistics are included, that describe the participant's ability to reach and touch several targets, this includes mean movement time and the classification of target acquisitions such as successful hits, hand loses, overshooting the target, and timeouts of targets. Compared to the objective performance statistics in the experiment with able-bodied participants additional data statistics are included, new (N) and exist (E) target acquisition performance statistics are described below:

- *Hand loses* (N) – when the user's hand has left the Leap Motions Controllers' tracking space.
- *Overshoots (OS)(N)* – occasions when the users have moved beyond the object, missing it and having to correct their movement trajectory to hit the target.
- *Timeouts (N)* – when the user has failed to hit the target after a 10 second period.
- *Mean MT* (E) – the average time it takes the participant to reach and touch a target.
- *Hits* (E) – the number of successful target acquisitions recorded by the user without losing their hand (hand loses), overshooting, or timing out.

Over the course of the experiment all users increased their number of successful hits, all users also decreased the number of hand loses occurrences, and 4 out of 5 participants had a reduced number of timeouts. This seems to suggest that users had learned and understood enough about the system to improve movement control within the tracking space enough to be able to reduce hand loses, become quicker, and to reduce timeouts. Most of the participants increased the number of overshoots over time, suggesting that user movement was less controlled – perhaps indicating that they were more fatigued or more bored/careless. However, this increase in overshoots may in part be explained by the decrease in time-outs and hand loses. This latter characteristic suggests that the user's movements seem to have been more controlled and as a result more of the targets the user acquired may have become overshoots (Figure 6-8) rather than timeouts and hand loses.

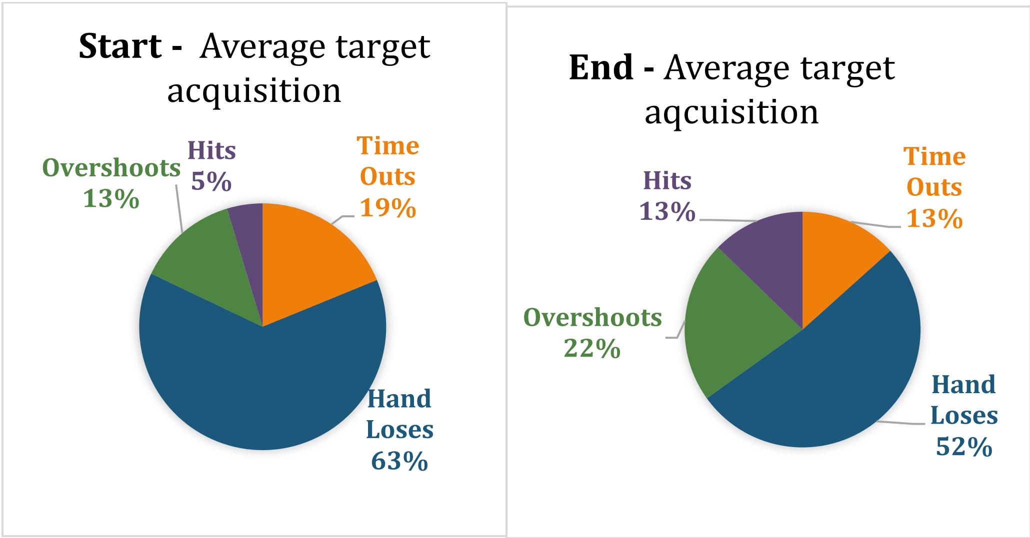



**Figure 6-8: Comparison of target acquisition over-time**

Nonetheless, the increase in overshoots suggests most users still didn't have enough accuracy in classifying target acquisition as successful hits. It might be considered an improvement in target acquisition performance if Time-outs and Hand-loses are reduced at the expense of increased Overshoots. It was expected that hand loses would be high due to the limited motor skills of the stroke patients. However, the decrease in the number of hand-loses by the end of the experiments shows that stroke patients were improving the accuracy of their movements. It is worth noting that hits and hand loses are a coarse measurement of target acquisition and that overshoots and timeouts provide additional information about the user's movement. However, ideally, all three of these statistics would be reduced while hits increase. From post-experiment questionnaires, despite all users having ten-minutes to train, users still felt they improved their target acquisition performance by the end of the experiment. All users also mentioned that they became fatigued during the experiment.

**Table 6-4: All participant user profiles over the course of the experiment**

| User | 2002 | 2003 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|
| START - Distribution | | | | | |
| Standard Deviation | 2.199 | 2.006 | 1.869 | 1.269 | 1.485 |
| Kurtosis | 0.929 | 1.497 | 3.496 | 2.125 | 6.242 |
| Skewness | 1.211 | 1.371 | 1.907 | 1.297 | 2.060 |
| END - Distribution | | | | | |
| Standard Deviation | 1.546 | 0.886 | 1.583 | 1.752 | 2.054 |
| Kurtosis | 4.246 | 0.028 | 0.466 | 3.206 | 2.138 |
| Skewness | 1.878 | 0.780 | 0.776 | 1.637 | 1.518 |
| START - Regression | | | | | |
| R2 | 0.040 | 0.122 | 0.064 | 0.300 | 0.283 |
| P-Value | 2.14E-01 | 1.58E-02 | 1.08E-01 | 1.94E-04 | 4.57E-05 |
| Intercept (a) | 1.041 | 0.333 | 0.901 | -2.008 | -1.211 |
| Gradient (b) | 1.222 | 1.633 | 1.274 | 2.192 | 1.840 |
| Sin coefficient (c) | -0.290 | -0.286 | -0.814 | 2.483 | 3.766 |
| END - Regression | | | | | |
| R2 | 0.196 | 0.016 | 0.526 | 0.139 | 0.224 |
| P-Value | 2.84E-05 | 5.40E-01 | 4.43E-12 | 3.98E-02 | 3.40E-04 |
| Intercept (a) | -0.235 | 1.833 | -1.957 | -0.998 | -3.441 |
| Gradient (b) | 0.380 | -0.019 | 4.165 | 1.433 | 3.068 |
| Sin coefficient (c) | 3.474 | -0.474 | -2.515 | 2.674 | 2.652 |
| Performance | | | | | |
| Targets Hit (1080) | 108 | 81 | 81 | 81 | 81 |
| Start Hits | 1 | 1 | 18 | 5 | 1 |
| End Hits | 14 | 3 | 30 | 7 | 8 |
| % Change Hits | +1300% | +200% | +67% | +40% | +700% |
| Start Mean MT | 2.846 | 2.935 | 2.741 | 2.827 | 3.418 |
| End Mean MT | 1.862 | 1.635 | 4.136 | 2.678 | 2.838 |
| % Change Mean Time | -35% | -44% | +51% | -5% | -17% |
| Start hand loses | 103 | 75 | 27 | 69 | 79 |
| End hand loses | 78 | 27 | 23 | 62 | 62 |
| % Change Hand loses | -24% | -64% | -15% | -10% | -22% |
| Start OS | 32 | 5 | 31 | 5 | 1 |
| End OS | 15 | 52 | 24 | 8 | 9 |
| % Change OS | -53% | +940% | -23% | +60% | +800% |
| Start Timeouts | 31 | 14 | 11 | 30 | 18 |
| End Timeouts | 9 | 1 | 8 | 34 | 15 |
| % Change Timeouts | -71% | -93% | -27% | +13% | -17% |
| User | | | | | |
| Motricity index (100) | 64 | 64 | 60 | 60 | 76 |
| Mini-mental (10) | 10 | 7 | 6 | 10 | 7 |
| Star cancellation test (56) | 48 | 52 | 54 | 56 | 56 |

### 6.5.1.1 PARTICIPANT 2002

#### *6.5.1.1.1 EVALUATING FITTS LAW VARIANTS*

Evaluation of the Fitts Law variants for user 2002 (Table 6-5) showed that by the end of the experiment, all equations decreased the values of the regression line gradient showing that the participant was finding the difficulty of the tasks easier, taking less time to complete the target acquisition tasks over different distances. The multiple regression approach had the most significant decrease in regression line gradient. The $R^2$ value for four of the five Fitts Law variants reduced showing that it explained less of the user’s movement. However, multiple regression increased in R2 value explaining more of the user's movement, therefore, having higher predictability from the model. Overall, multiple regression provides a more suitable model for prediction and identifying performance improvements for participant 2002, and it is possible the movement angle had a larger impact on the user’s movement as an independent variable.

**Table 6-5: Regression results of five of the popular Fitts Law equations for participant 2002.**

| User | 2002 | | | | |
|---|---|---|---|---|---|
| | **Murata** | **Fitts** | **Welford** | **Shannon** | **Multiple** |
| Start | | | | | |
| R2 | 0.039 | 0.043 | 0.040 | 0.041 | 0.040 |
| Intercept (a) | 0.974 | 1.396 | 0.916 | 1.548 | 1.041 |
| Gradient (b) | 1.135 | 0.743 | 1.220 | 0.993 | 1.222 |
| End | | | | | |
| R2 | 0.029 | 0.031 | 0.030 | 0.030 | 0.196 |
| Intercept (a) | 0.296 | 0.542 | 0.229 | 0.732 | -0.235 |
| Gradient (b) | 0.926 | 0.649 | 1.006 | 0.831 | 0.380 |

#### *6.5.1.1.2 USER PROFILE ANALYSIS*

Participant 2002 profile in Table 6-4, began the experiment with a weak movement performance profile according to the results, showing a large spread of data points from the regression line. Over the course of the experiment, she showed improvements in her movement performance. The regression model became much more significant (Start: 2.14E-01, End: 2.84E-05), with an $R^2$ value that increased 390% to indicate improved predictability, the regression line gradient reduced over time indicating improved acquisition performance performing across all IDs. Participant 2002 had less variation in movement times per ID, indicated by a lower standard deviation, higher positive kurtosis and skew, showing less spread of movement times from the regression line with occasionally unexplained high movement times. Most movement times were below the regression line suggesting a majority of fast, effective movement times; mean MT also showed that the user was 35% quicker than the start of the experiment. The positive kurtosis was higher, due to occasionally higher MT shown in Figure 6-9. Hits increased by 1300%, Hand loses decreased by 24%, Overshoots decreased by 53%, and she also recorded 71% fewer Timeouts by the end of the experiment. This suggests that the user's target acquisition results had improved limb control while also being quicker, resulting in a more reliable regression model and user profile that was better at predicting the user's future task difficulty. From the questionnaires given to the participants after the experiment which are shown in Table 6-6. The participant stated that she began to tire over the course of the experiment, but she felt her performance improved; it is possible that the user had improved capability before the end of the experiment, but fatigue occurred causing a decline in performance. However, fatigue appears not to be so significant that the user profile became unreliable. Fatigue may have been exasperated to the long period spent using the system (1hr 55 mins), in comparison to the recommended rehabilitation guidelines of a minimum of 45 minutes. Real-Time analysis of the user profiles would identify factors like this in real time and be able to adapt more rapidly. Observation and user feedback in Table 6-6 shows that the investigator and the participants' subjective views support the user's movement profile data. Despite this user having one of the lowest star cancellation scores showing increased spatial neglect in their reaching space, it seems this did not significantly impact their ability to improve movement and target acquisition performance.

**Table 6-6: Participant 2002 questionnaire and interview results**

| Qualitative Analysis | | |
|---|---|---|
| Experiment length | | 1 hr 55 mins |
| Became Tired | | YES |
| Became Frustrated | | NO |
| Became Bored | | NO |
| Perceived Performance (10/10) | START | 3 |
| | END | 7 |
| Observations | Feedback | |
| • Initially, found it difficult to learn interactions | • High contrasting colours very good for vision | |

| | |
|---|---|
| • Had to be reminded of instructions on how to target the origin<br>• Over-time she improved her interaction<br>• Smaller objects without cues seemed very difficult<br>• Higher objects seemed more difficult | • Origin very difficult to obtain<br>• Oculus better than the screen<br>• Oculus had better contrast<br>• Small objects harder to see<br>• Found it hard to focus near the end<br>• Smaller objects were more difficult<br>• Focused on the colour of the object more to determine the location<br>• Darker colours where harder to see |

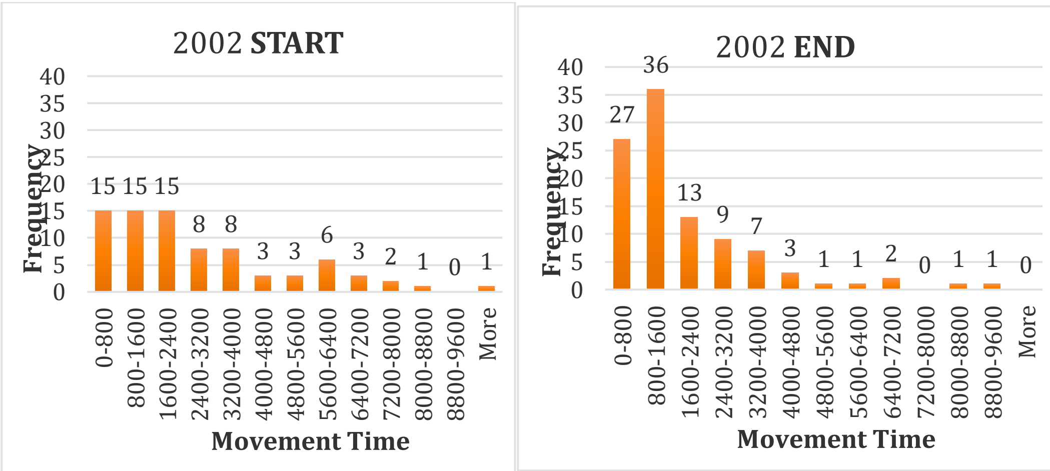



**Figure 6-9: 2002's histograms of start and end movement times.**

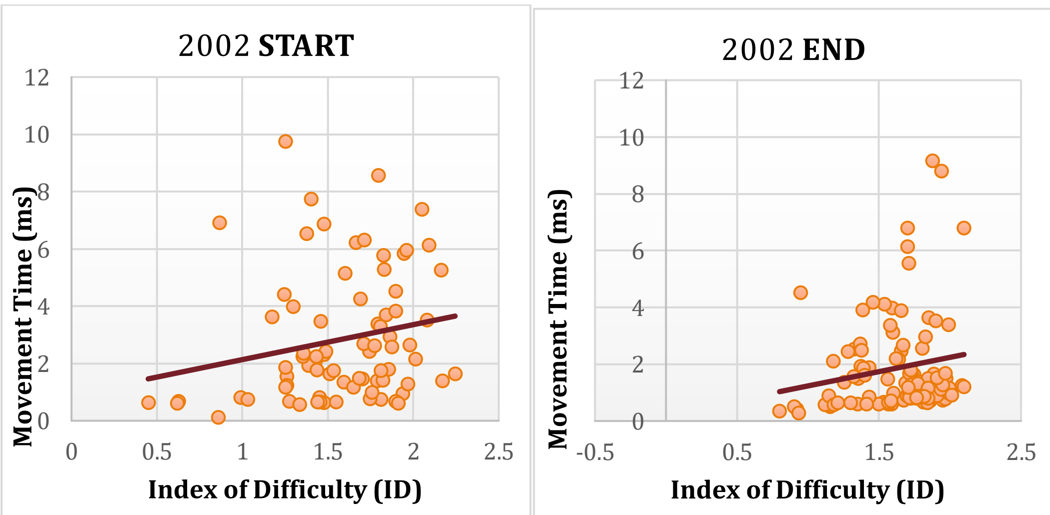



**Figure 6-10: 2002's Murata's multiple start and end regression lines**

## 6.5.1.2 PARTICIPANT 2003

### *6.5.1.2.1 EVALUATING FITTS LAW VARIANTS*

Evaluation of the Fitts law model variants (Table 6-7) for user 2003 shows that for all equations the user movements began with a steep regression line gradient and reduced to an almost zero suggesting that the user became more consistently fast across all difficulties of the task – this is an indicator of improved performance. Multiple regression approach had a close to zero gradient. $R^2$ values for all equations decreased to be close to zero, and the user's movement was so varied that they could not be reliably modelled with Fitts Law, it would be recommended that when Fitts Law is unreliable, the user is adapted through the other statistics gathered.

**Table 6-7: Regression results of Fitts Law equations for participant 2003.**

| **User** | **2003** | | | | |
|---|---|---|---|---|---|
| | **Murata** | **Fitts** | **Welford** | **Shannon** | **Multiple** |
| Start | | | | | |
| $R^2$ | 0.121 | 0.109 | 0.121 | 0.117 | 0.122 |
| Intercept (a) | 0.262 | 1.139 | 0.210 | 1.128 | 0.333 |
| Gradient (b) | 1.546 | 0.883 | 1.646 | 1.302 | 1.633 |
| End | | | | | |
| $R^2$ | 0.000 | 0.001 | 0.000 | 0.001 | 0.016 |
| Intercept (a) | 1.579 | 1.520 | 1.558 | 1.566 | 1.833 |
| Gradient (b) | 0.031 | 0.052 | 0.044 | 0.046 | -0.019 |

### *6.5.1.2.2 USER PROFILE ANALYSIS*

In Table 6-4, at the end of the experiment participant 2003's movement performance seemed to have deteriorated further. The participant improved their target acquisition performance. However, it seems that faster movements have reduced coordination resulting in a less predictable regression model. Their mean MT was 44% faster; this was the largest increase in movement speed compared to all users. Timeouts reduced by 93% and hand loses decreased by 64% suggesting they had more control of their movement by the end of the experiment. Overshoots increased by 940% showing that the majority of the data points included in the regression model where considered overshoots (52/81) this may indicate that although the user's movements had improved enough to speed up their movements while remaining in the hand tracking space; the faster movements may have produced more overshoots and less coordination.

**Table 6-8: Participant 2003's questionnaire and interview results.**

<table>
<tr><th colspan="3">Qualitative Analysis</th></tr>
<tr><td colspan="2">Experiment length</td><td>1 hr 35 mins</td></tr>
<tr><td colspan="2">Became Tired</td><td>YES</td></tr>
<tr><td colspan="2">Became Frustrated</td><td>NO</td></tr>
<tr><td colspan="2">Became Bored</td><td>NO</td></tr>
<tr><td rowspan="2">Perceived Performance (10/10)</td><td>START</td><td>3</td></tr>
<tr><td>END</td><td>7</td></tr>
<tr><th colspan="2">Observations</th><th>Feedback</th></tr>
<tr><td colspan="2"><ul><li>Origin very difficult to select</li><li>Further resting needed in the first level</li><li>Observed an improvement closer to the end of the first level</li><li>Furthest objects seemed to be very difficult</li><li>Experienced vast improvement with Oculus</li><li>After Oculus a big improvement is seen in movement performance - with medium objects at least</li><li>Started to fatigue around level 7</li></ul></td><td><ul><li>Far away objects are more difficult</li><li>Origin very difficult to obtain</li><li>Oculus is better</li></ul></td></tr>
</table>

The descriptive statistics of the residuals show kurtosis moving towards a normal distribution indicating there was equally as many movement times in the tails as the peak and a lower skewness indicates a more symmetric and even spread of data points along the regression line, this may explain the almost zero and negative regression line gradient value (Figure 6-12). The histograms of the user movement times in Figure 6-11 showed that by the end of the experiment the user's movement was faster (positively skewed) and the small spread of movements. Her user profile indicates that she has improved target acquisition with significantly fewer Timeouts and Hand loses. However, she became faster (Mean MT), possibly causing more overshooting, which seems to have reduced movement accuracy and coordination seen in the regression model (Figure 6-12) the predictability of the regression model. The user did mention they became tired during the experiment, the investigator also stated, she began to tire from level 7, but never bored or frustrated. Therefore, it may be possible that fatigue had caused the user to become more erratic in their movement which may have caused the faster and less coordinated movement in order to complete the experiment. Although the participant improved performance in certain aspects such as target acquisitions and she coincided with that in Table 6-8, it seems fatigue had a large impact on how the users' motor skills behaved.

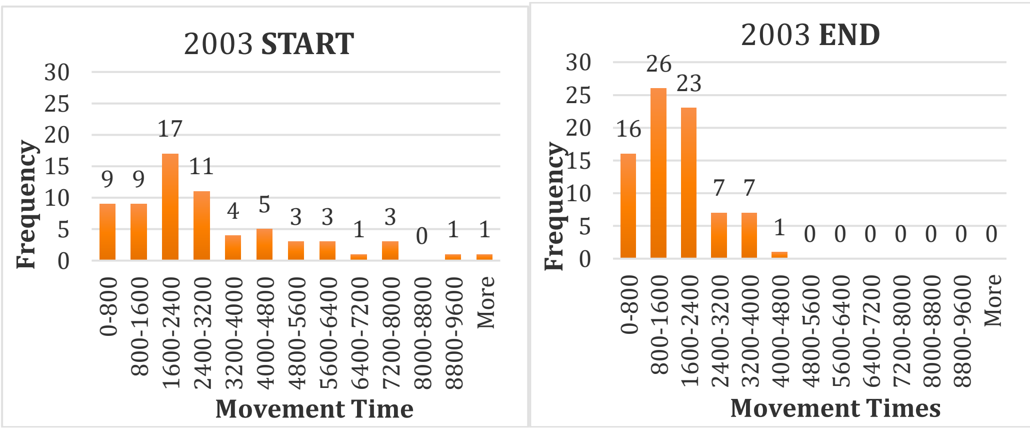



**Figure 6-11: 2003's histograms of movement time at start and end**

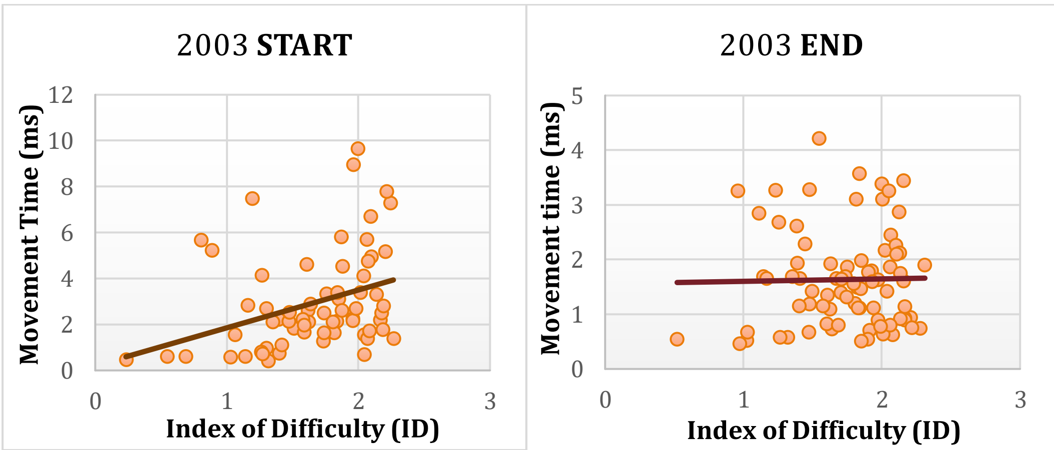



**Figure 6-12: 2003's Murata's multiple regression model at start and end**

### 6.5.1.3 PARTICIPANT 2006

#### *6.5.1.3.1 EVALUATING FITTS LAW VARIANTS*

Comparing all Fitts Law variants (Table 6-9), user 2006 increased their regression line gradient value indicating that this user became slower, e.g. End Mean MT in Table 6-4. $R^2$ values increased significantly for all equations and results from all equations produced similar regression results. However, the multiple regression equation seems to produce better predictability of the user's movement regarding the higher $R^2$ value at both the start and end of the experiment.

**Table 6-9: Regression results of Fitts Law equations for participant 2006**

| User | 2006 | | | | |
|---|---|---|---|---|---|
| | **Murata** | **Fitts** | **Welford** | **Shannon** | **Multiple** |
| Start | | | | | |
| $R^2$ | 0.053 | 0.055 | 0.056 | 0.056 | 0.064 |
| Intercept (a) | 0.722 | 1.069 | 0.625 | 1.264 | 0.901 |
| Gradient (b) | 1.152 | 0.795 | 1.260 | 1.038 | 1.274 |
| End | | | | | |
| $R^2$ | 0.453 | 0.425 | 0.452 | 0.444 | 0.526 |
| Intercept (a) | -2.943 | -1.357 | -3.105 | -0.895 | -1.957 |
| Gradient (b) | 3.907 | 2.522 | 4.179 | 3.385 | 4.165 |

#### *6.5.1.3.2 USER PROFILE ANALYSIS*

At the start of the experiment, 2006's profile (Table 6-4) indicated low predictability with Fitts Law ($R^2$: 0.061) with low significance from the regression model, and descriptive statistics of the residuals suggesting high variability of data point positions from the regression line. By the end of the experiment, the user had become 51% slower and more accurate, with a decrease in Time Outs (27% less), Overshoots (23% less), Hand loses (15% less) and a 67% increase in successful Hits. Regression statistics improved with a significantly higher $R^2$ value ($R^2$: 0.526), explaining more variation of the user's movement. MT performance improved across IDs with a steeper regression line evident, and the user's Mean MT at the end is smaller. Descriptive statistics also showed that the user's movement was more controlled with an improvement in all movement performance measures. Kurtosis moved closer to zero (normal distribution) suggesting that fewer extreme movement time values occurred, skew decreased towards zero indicating that values were evenly spread above and below the regression line. Standard deviation decreased suggesting that the spread of values across the regression line was getting smaller. A kurtosis and skew moving closer to the normal distribution and standard deviation decreasing suggests a more consistent and controlled movement. From the data, it seems that user 2006 slowed down and this has resulted in a more predictable user profile. Slowing down in the case of this user has allowed them to control their movement better and improve target acquisition performance. The same behaviour was observed with abled-bodied user 1019 in chapter 5.4.1.2. Qualitative analysis (Table 6-10) showed that 2006 also felt that she had improved her performance. This was despite the participant mentioning that she became tired, frustrated and bored during the experiment. It is important to note from this experiment that impaired users could improve, despite finding the exercise challenging. Feeding this information back to users over time could help improve engagement, as could improving aspects of the exercise such as session length and adding more fun games. Another feature of behaviour that is evident in both impaired and healthy user experiments is that slowing down can be important for improving performance. Adapting the system difficulty and providing in-VR feedback to encourage a person to slow down when performance is poor could be of benefit. VR games with game dynamics that encourage slower play may also help – i.e. less focus on speed in the feedback and rewards systems. Though target hits are the most important feature of the interactive system in this experiment, this may not have been as evident as it could be.

**Table 6-10: Participant 2006's Questionnaire and interview results.**

<table>
<tr><th colspan="3">Qualitative Analysis</th></tr>
<tr><td colspan="2">Experiment length</td><td>2 hrs 35 mins</td></tr>
<tr><td colspan="2">Became Tired</td><td>YES</td></tr>
<tr><td colspan="2">Became Frustrated</td><td>4/5</td></tr>
<tr><td colspan="2">Became Bored</td><td>4/5</td></tr>
<tr><td rowspan="2">Perceived Performance (10/10)</td><td>START</td><td>4</td></tr>
<tr><td>END</td><td>7</td></tr>
<tr><th colspan="2">Observations</th><th>Feedback</th></tr>
<tr><td colspan="2">• Suffers from short-term memory loss<br>• Took additional breaks during 1st level<br>• Became hot window had to be open<br>• Needed support from the other hand at times<br>• Additional feedback needed "bring it towards your face", "pretend you're going to eat something"(selecting the origin object)<br>• With Oculus there was a lot of back movement<br>• Started to fatigue on the last level</td><td>• "I don't Like this game it's very annoying."<br>• Oculus better than screen "you see the objects clearer."<br>• Small origin objects where hard to obtain<br>• After your instructions, it helped me hits the objects better</td></tr>
</table>

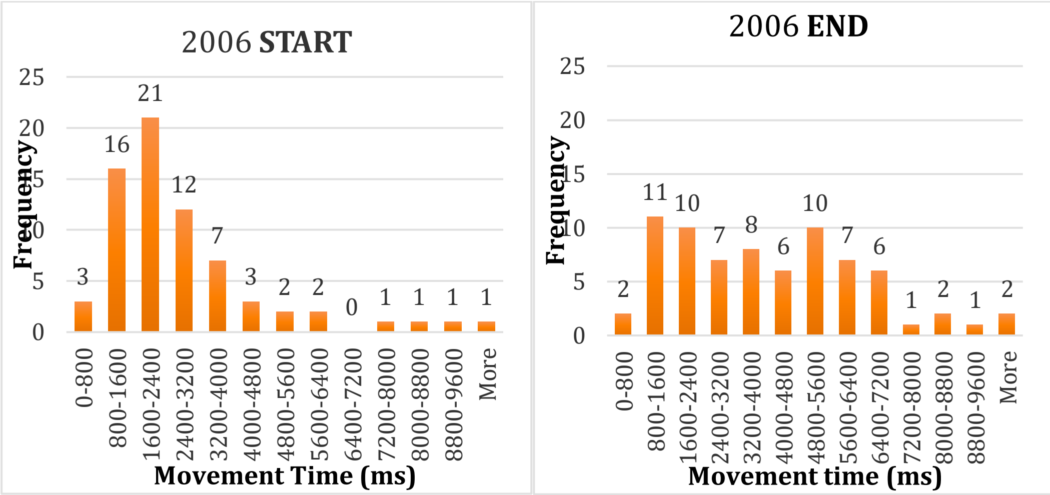



**Figure 6-13: 2006's histograms of movement time at the start and end of the experiment.**

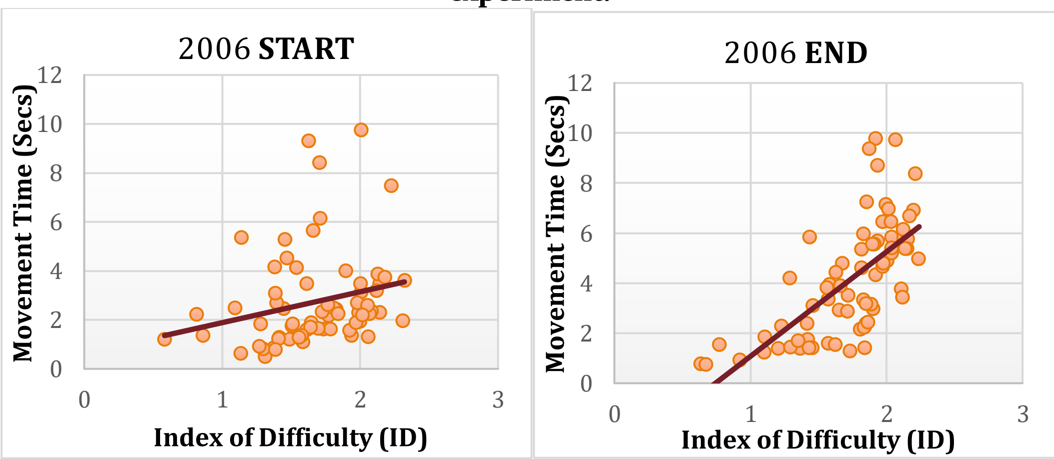



**Figure 6-14: 2006's Murata's multiple regression model at the start and end of their experiment.**

## 6.5.1.4 PARTICIPANT 2007

### *6.5.1.4.1 EVALUATING FITTS LAW VARIANTS*

Analysing the range of Fitts law models for user 2007 in Table 6-11, the regression line gradient became smaller for all equations by the end of the experiment, indicating faster movement. However, all equations had reductions in $R^2$, showing greater variability in movements per ID. The multiple regression model began with a higher $R^2$ value than the other equations and remained higher than the other models by the end of the experiment. This may be due to the introduction of the movement angle having a larger impact on the user's movement.

**Table 6-11: Regression results of five of the popular Fitts Law equations for participant 2007.**

| User | 2007 | | | | |
|---|---|---|---|---|---|
| | Murata | Fitts | Welford | Shannon | Multiple |
| Start | | | | | |
| R2 | 0.181 | 0.183 | 0.184 | 0.183 | 0.300 |
| Intercept (a) | -0.453 | -0.050 | -0.572 | 0.385 | -2.008 |
| Gradient (b) | 1.826 | 1.323 | 1.974 | 1.654 | 2.192 |
| End | | | | | |
| R2 | 0.018 | 0.010 | 0.017 | 0.014 | 0.139 |
| Intercept (a) | 1.075 | 1.611 | 1.097 | 1.629 | -0.998 |
| Gradient (b) | 0.878 | 0.480 | 0.904 | 0.694 | 1.433 |

### *6.5.1.4.2 USER PROFILE ANALYSIS*

In Table 6-4, participant 2007 began the experiment with a significant and good predictive regression model; descriptive statistics showed less variation in movement behaviour. By the end of the experiment, the user’s mean MT was 5% quicker, and the regression line gradient is decreasing over time (Figure 6-16) reflecting generally faster movements by the end. There was also a 40% increase in successful hits from the start of the experiment. However, Timeouts and Overshoots increased suggesting that the user’s movements were becoming less careful and that the overall accuracy of movement was declining. The regression model’s $R^2$ decreasing value backs up this analysis, as does the increase in standard deviation. Kurtosis and skew increased positively indicating a tendency to overshoot, or for some acquisitions to take much longer than others (Figure 6-15). User 2007’s user movement profile seems to indicate that she was becoming tried but did not decline enough to produce an unreliable profile according to the significance of the regression model. The user profile could be used to identify the need to make tasks easier to reduce the tiredness or allow the person to rest. 2007 felt that she improved in performance over time but became tired (Table 6-12) which correlates with the user’s movement profile. The participant also expressed that they became a little bored and frustrated, which may be reflected in the reduced $R^2$ yet gained improvements in other statistics.

**Table 6-12: Participant 2007’s Questionnaire and semi structured interview results.**

<table>
<tr><th colspan="3">Qualitative Analysis</th></tr>
<tr><td colspan="2">Experiment length</td><td>1 hr 24 mins</td></tr>
<tr><td colspan="2">Became Tired</td><td>YES</td></tr>
<tr><td colspan="2">Became Frustrated</td><td>2/5</td></tr>
<tr><td colspan="2">Became Bored</td><td>2/5</td></tr>
<tr><td rowspan="2">Perceived Performance (10/10)</td><td>START</td><td>4</td></tr>
<tr><td>END</td><td>8</td></tr>
<tr><th colspan="2">Observations</th><th>Feedback</th></tr>
<tr><td colspan="2"><ul>
<li>Found interaction difficult, origin very difficult to obtain</li>
<li>Took additional breaks on level 1</li>
<li>Near the end of the experiment adopted a fist gesture, it seemed to improve the interaction</li>
<li>Furthest objects where a consistent problem but still attempted to acquire them</li>
<li>A lot of upper body movement</li>
<li>Very willing mentality, very willing to try new rehabilitation techniques</li>
</ul></td><td><ul>
<li>She mentioned concentration levels were reducing and tiredness was setting in</li>
<li>She said she briefly got distracted by noises outside the room</li>
<li>Trouble seeing the object because my hand blocked it.</li>
<li>Mentioned that learning where the origin would be in the real world helped through practice</li>
<li>Her children would encourage her to use it if it helped rehab</li>
<li>Preferred Oculus "Oculus definitely" felt she didn’t get as distracted while wearing the Oculus</li>
<li>Felt less tired with Oculus in the shoulder</li>
<li>Leap without VR is difficult because of occlusion</li>
<li>Did see improvement without Oculus but even more with Oculus</li>
<li>Erratic hand movement (tracking failure) was distracting</li>
<li>Shadows had no difference in my performance</li>
<li>Last level very tiring</li>
</ul></td></tr>
</table>

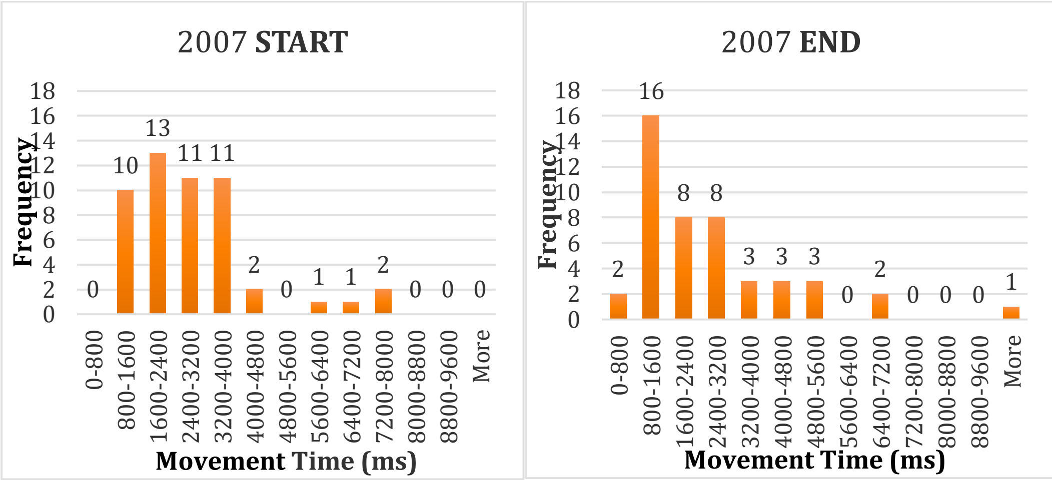



**Figure 6-15: 2007's histograms of movement time at the start and end of the experiment.**

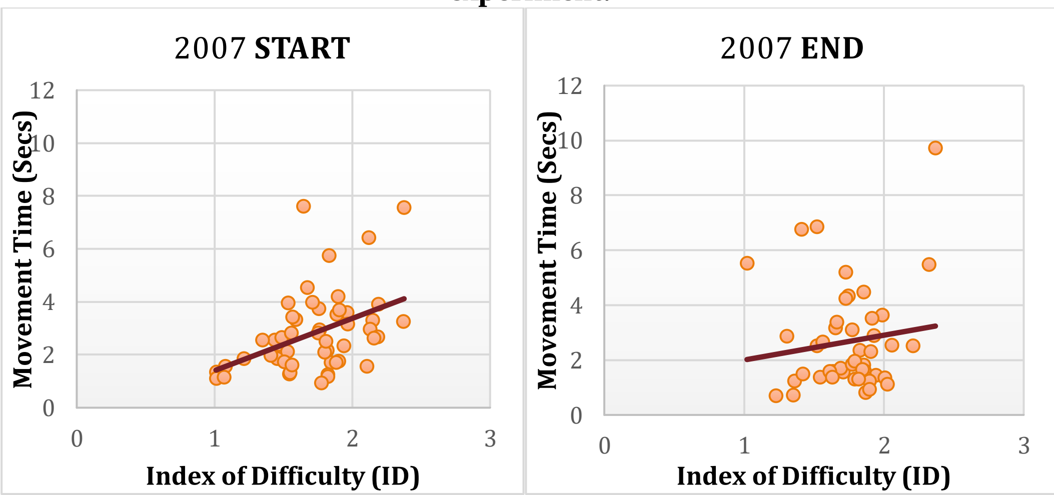



**Figure 6-16: 2007's Murata's multiple regression model at the start and end of their experiment.**

### 6.5.1.5 PARTICIPANT 2008

#### *6.5.1.5.1 EVALUATING FITTS LAW VARIANTS*

For all equations (Table 6-13), 2008's regression line gradient increased over time showing a greater range of MTs between small/large IDs. However, End Mean MT (Table 6-4) was smaller than that at the beginning by over half a second (0.580 secs faster). Further analysis of the user profile may be required to explain the behaviour of the regression line gradient values. $R^2$ values at the beginning were low for four of the equations, apart from the multiple regression model which had a significantly higher $R^2$ value than the other four equations. By the end of the experiment, the four equations exhibited lower $R^2$ values for regression. The multiple regression model $R^2$ decreased a little but remained higher than the other four models.

**Table 6-13: Regression results of five of the popular Fitts Law equations for participant 2008.**

| User | 2008 | | | | |
|---|---|---|---|---|---|
| | Murata | Fitts | Welford | Shannon | Multiple |
| Start | | | | | |
| R2 | 0.052 | 0.056 | 0.053 | 0.054 | 0.283 |
| Intercept (a) | 1.442 | 1.589 | 1.381 | 1.902 | -1.211 |
| Gradient (b) | 1.055 | 0.805 | 1.137 | 0.974 | 1.840 |
| End | | | | | |
| R2 | 0.169 | 0.162 | 0.167 | 0.165 | 0.224 |
| Intercept (a) | -1.451 | -0.816 | -1.533 | -0.298 | -3.440 |
| Gradient (b) | 2.364 | 1.667 | 2.514 | 2.100 | 3.068 |

#### *6.5.1.5.2 USER PROFILE ANALYSIS*

At the beginning of the experiment 2008 produced a performance that could reliably be modelled through multiple regression. Descriptive statistics that suggest that the user's movements were mostly consistent, with a high positive kurtosis and positive skew indicating a tendency to overshoot. This supports the investigator's comments in Table 6-14, where they said the participant was "*very good at the beginning of the experiment. However, the participant had more capable motor skills in the arm than other participants*". At the end of the experiment, the participant 2008 reduced their number of Hand loses (22%) and Timeouts (17%). However, though hits improved (700%), overshoots (800%) also increased. It seems that although the participant had improved movement control to reduce the Timeouts and Hand loses and increase successful hits, they may have tired slightly resulting in an increase in the number of overshoots. Regression statistics may explain this further; the $R^2$ had a small decline (Start: 0.283, End: 0.224) but the regression model remained significant. The regression line gradient increased giving a steeper regression line showing that the user was taking longer to complete the movement when hitting a target with higher IDs. However, Mean MT showed that the user was 17% faster by the end of the experiment. Figure 6-17 shows the histogram of the user's movement times at the end, had fewer slow movement times. However, the slow movements that were recorded tended to be higher than at the start of the experiment. These outliers seemed to have an impact on the regression line, moving it up and producing a steeper regression line gradient (Figure 6-18). These outliers are potentially a useful indicator of fatigue, and so are important to note and use within a future adaptive model. Regression may be more effective by eliminating these outliers. However, it is important to not only use the regression line gradient for adaptation but to profile a person using a range of factors. Kurtosis and skew reduced over time, having smaller but still positive values. This indicates an improvement in capability generally, which seems to be at odds with the user's increase in overshooting. Though it should be noted that 2007 also decreased Hand loses, which improved the overall statistics. On the other hand, as they became more tired, it can be seen that a few target acquisitions took much longer than the average. The standard deviation of the user profile also increased by 0.569 seconds, which may also have been a result of fatigue – indicated less overall control. Feedback from the user was that they felt they tired during the experiment, and also that they also felt frustrated. A reduction in engagement, along with increased fatigue could affect performance. Nonetheless, regression could still be used to predict future MT based on ID.

**Table 6-14: Participant 2008's Questionnaire and semi structured interview results.**

| Qualitative Analysis | | |
|---|---|---|
| Experiment length | | 1 hr 6 mins |
| Became Tired | | YES |
| Became Frustrated | | 4/5 |
| Became Bored | | NO |
| Perceived Performance (10/10) | START | 2 |
| | END | 8 |
| Observations | | Feedback |

| | |
|---|---|
| • Hand occlusion an issue<br>• Very good at the beginning of the experiment but. However, the participant did seem to have more movement but had more capable motor skills in the arm than other participants<br>Additional breaks needed in the 1st level<br>• Occasionally used other arm to support due to tiredness | • Felt she was getting frustrated at times<br>• A lot easier with the Oculus<br>• Small objects hard to see due to poor vision |

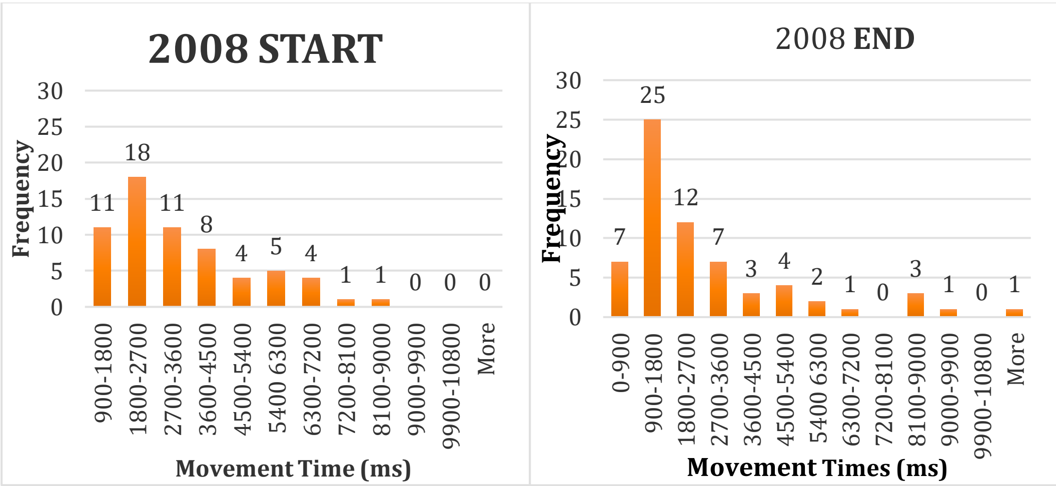



**Figure 6-17: 2008's histograms of movement time at the start and end of the experiment.**

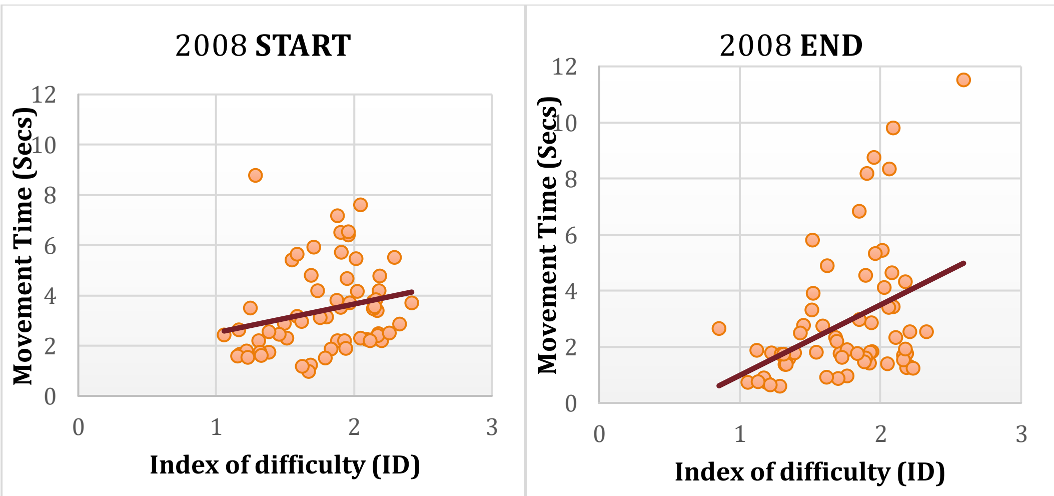



**Figure 6-18: 2008's Murata's multiple regression model at the start and end of their experiment.**

## 6.5.2 USABILITY

The usability evaluation of TAGER with upper limb impaired participants was conducted through a semi-structured interview and questionnaires post-experiment. Questions were related to the VR headset, Fatigue and movement performance (APPENDIX J). The SUS questionnaire (APPENDIX O) for assessing the general usability of the system was also given to the participant. An average score of 68 was recorded through the SUS questionnaire. A score above 70 is considered above average for the usability of a system.  However, 75% of the participants felt frustrated during the experiment. Predominantly, most participants were frustrated by the difficulty to hit the origin target closest to the user, and the smaller objects were very frustrating as they were harder to see. All users did become tired; this is most likely due to the long period spent using the system. Some participants expressed difficulty in target acquisition due to the participant's real hand occluding the PC monitor; this was seen when the user was wearing the Leap Motion Controller only on the head without a VR headset. Two of the users required extra guidance occasionally to target the origin object, but the users felt that they improved after practice.

### 6.5.2.1 VR HEADSET

All participants said that they would rather wear the VR headset because it was a more enjoyable experience. Two of the five participants mentioned that the Oculus gave them better clarity to see the objects. For example, one participant commented that “*with the Oculus, you see the objects clearer*". All participants stated that they felt their movement performance had improved with the VR headset, participants rated their performance regarding accuracy and speed on a 5-point scale one being improved and five being improved vastly. An average score of 4.6/5 was recorded for accuracy and 4.2/5 for speed. One participant commented she got distracted by her surroundings, but when wearing the VR headset, she said: "*I did not get as distracted with the headset*”. It seems that users found their experience with the VR headset more favourable compared to the standard PC monitor and wearing only the Leap Motion Controller on the head.

In this experiment, it was possible to compare user profiles between the use of the monitor and VR headset (Table 6-15). Performance statistics show that all users increased the number of successful hits while using the VR headset, and Hand loses and Timeouts also decreased significantly. Mean MT showed that all users became quicker when the VR headset was worn. Descriptive statistics on the residuals of the regression line seem to show more control of user movement; standard deviation decreased significantly for all users, kurtosis produced higher positive values for all users and majority of participants recorded higher positive values in Skew. This shows that the participant's movement times were less spread out from the regression line and user performance was generally more consistent. However, they produced more noticeable outlier movement times more often, and 4 of the 5 participants increased their number of overshoots when using the VR headset. From the regression statistics, it can be seen that four out of the five participants reduced the steepness of the regression line when wearing the VR headset in comparison to using with the 2D monitor, and the other participant had a similar gradient result to the PC monitor use. Participants seemed to have better MT times across a range of IDs while using the VR headset – corroborated by a reduction in Mean MT. Two out of five users had increased $R^2$ values for regression. The other three participants (2003, 2007, 2008), whose performance did not show an improvement in $R^2$ but remained significant. The three participants recorded very high kurtosis values (2003=8.192, 2007=13.946, 2008=18.450), which impacted regression quality. An example is participant 2008's regression graph (Figure 6-20) while wearing the VR headset showed that 2008’s movement times were closer to the regression line with occasional outliers which may explain the high kurtosis. This would suggest that eliminating outliers from the regression would increase $R^2$ and explain more of the participant's variation in movement. The results suggest that the VR headset improves user control of movement more often and that users were quicker with the VR headset. This seems to support participants’ subjective opinions on their performance in accuracy and speed with the VR headset.

**Table 6-15: The user movement profiles of all participants.**

| User | 2002 | 2003 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|
| No VR - Descriptive | | | | | |
| Standard Deviation | 2.199 | 2.006 | 1.869 | 1.269 | 1.485 |
| Kurtosis | 0.929 | 1.497 | 3.496 | 2.125 | 6.242 |
| Skew | 1.211 | 1.371 | 1.907 | 1.297 | 2.060 |
| VR - Descriptive | | | | | |
| Standard Deviation | 0.654 | 0.695 | 1.447 | 1.083 | 0.849 |
| Kurtosis | 4.016 | 8.192 | 3.798 | 13.946 | 18.450 |
| Skew | 1.936 | 2.259 | 1.904 | 3.285 | 3.569 |
| No VR - Regression | | | | | |
| R2 | 0.040 | 0.122 | 0.064 | 0.300 | 0.283 |
| P-Value | 2.14E-01 | 1.58E-02 | 1.08E-01 | 1.94E-04 | 4.57E-05 |
| Intercept (a) | 1.041 | 0.333 | 0.901 | -2.008 | -1.211 |
| Gradient (b) | 1.222 | 1.633 | 1.274 | 2.192 | 1.840 |
| Sin coefficient (c) | -0.290 | -0.286 | -0.814 | 2.483 | 3.766 |
| VR - Regression | | | | | |
| R2 | 0.071 | 0.085 | 0.0713 | 0.233 | 0.140 |
| P-Value | 2.14E-02 | 3.57E-02 | 6.47E-02 | 1.23E-04 | 3.06E-03 |
| Intercept (a) | 0.358 | 0.826 | 0.465 | -1.930 | -0.017 |
| Gradient (b) | 0.576 | 0.364 | 1.296 | 1.456 | 0.853 |
| Sin coefficient (c) | -0.167 | -0.483 | -1.010 | 1.366 | 0.273 |
| Performance | | | | | |
| Targets Hit (1080) | 108 | 81 | 81 | 81 | 81 |
| Start Hits | 1 | 1 | 18 | 5 | 1 |
| End Hits | 19 | 6 | 31 | 26 | 45 |
| % Change Hits | +1800.00% | +500.00% | +72.22% | +420.00% | +4400.00% |
| Start Mean MT | 2.8455 | 2.935 | 2.741 | 2.82 | 3.418 |
| End Mean MT | 1.245 | 1.256 | 2.365 | 1.472 | 1.675 |
| % Change Mean Time | -56.23% | -57.28% | -13.72% | -47.94% | -51.00% |
| Start hand loses | 103 | 75 | 27 | 69 | 79 |
| End hand loses | 4 | 6 | 5 | 5 | 35 |
| % Change Hand loses | -96.12% | -92.00% | -81.48% | -92.75% | -55.70% |
| Start OS | 32 | 5 | 31 | 5 | 1 |
| End OS | 87 | 69 | 41 | 40 | 0 |
| % Change OS ONLY | +171.88% | +1280.00% | +32.26% | +700.00% | -100.00% |
| Start Time outs | 31 | 14 | 11 | 30 | 18 |
| End Time outs | 1 | 3 | 4 | 10 | 1 |
| % Change Time outs | -96.77% | -78.57% | -63.64% | -66.67% | -94.44% |
| User | | | | | |
| Motricity index 100/100 | 64 | 64 | 60 | 60 | 76 |
| Mini mental 10/10 | 10 | 7 | 6 | 10 | 7 |
| Star cancellation test 56/56 | 47 | 52 | 54 | 56 | 56 |

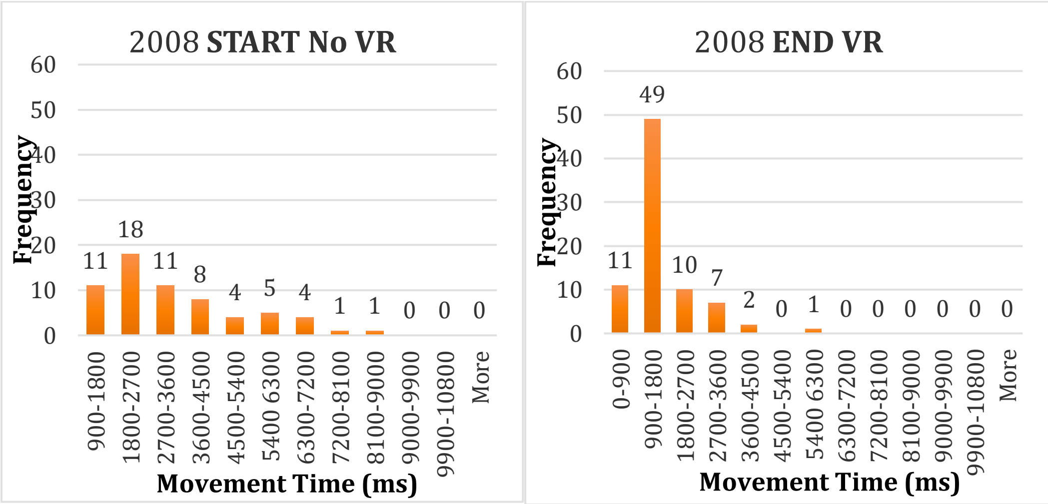



**Figure 6-19: 2008's histograms of movement time using the VR headset and without the VR headset.**

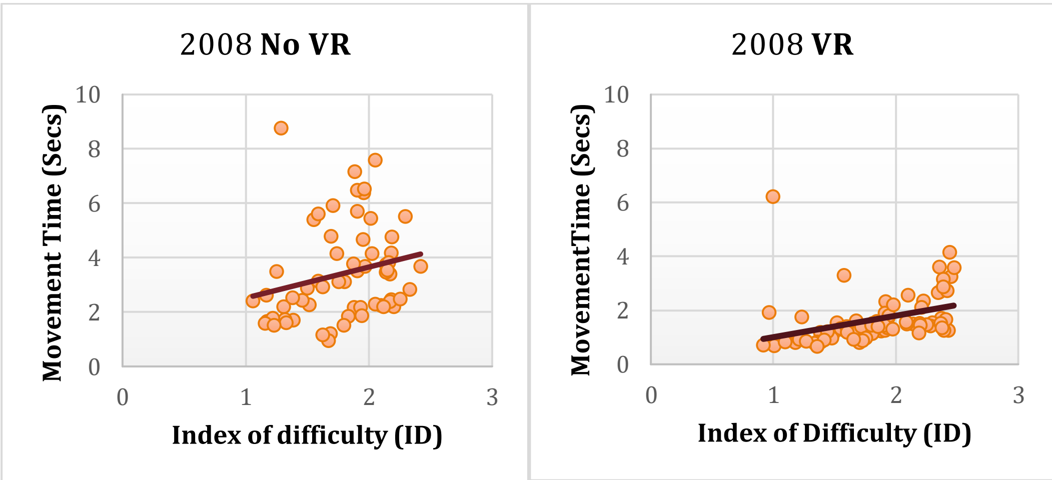



**Figure 6-20: 2008's Murata's multiple regression model when using the VR headset and without the VR headset.**

# 6.6 DISCUSSION

In this experiment, upper limb impaired participants used an evolved version of TAGER, a 3D VR reaching and touching exercise system. TAGER was evolved based on results from the previous study and feedback from the clinic and hospital visits. The experiment evaluates the design of TAGER as a reaching and touching exercise system for the motor recovery of the upper limbs with people after a stroke or traumatic brain injury. To investigate the suitability of Fitts Law and variants for modelling the user's movement for reaching and touching exercises with novel natural user interface devices and compare the results against the able-bodied users in the previous study. Evaluating the various versions of Fitts Law with each user found that all equations gave similar regression results regarding the regression line gradient and intercept values. However, Murata's multiple regression approach improved the $R^2$ values for all users compared to the other equations, explaining more of the user's movement variations. For the analysis of the user profiles, Murata's multiple regression approach was used as it produced the more appropriate model. In the study with able-bodied participants in Chapter 5, Murata's multiple regression approach was also the most appropriate for modelling movement of able-bodied participants.

Throughout the experiment, participants felt that they had improved their performance of the reaching and touching exercises inside TAGER, despite some participants experiencing levels of tiredness, boredom or frustration. This was supported by improvements in the target acquisition performance from the users' movement profile. Despite a demonstration and training session before the official TAGER experiment, some users were still learning, indicated by a weaker user profile at the start and an improved profile at the end. Some participants started with a strong user profile and produced a weak profile by the end; this indicates fatigue or a lack of interest in the exercises. Findings from able-bodied participants also found that users required more time to learn the actions involved and able-bodied participants also showed signs of fatigue even though they had complete mobility of their upper limbs and the same training session time as impaired participants. This validates the use of Fitts Law and this method of user profiling to identify the user movement behaviours and human factors of upper limb impaired participants.

As expected, participants with upper limb impairments were generally slower than the able-bodied participants, and there was a significant decrease in the number of successful hits in impaired users compared to able-bodied users, this improved when wearing the VR headset. Larger values in standard deviation and lower values in kurtosis were seen in impaired users compared to able-bodied users suggesting that there was a higher diversity of movement times which is expected from participants with limited upper limb mobility. On occasions, it was difficult to model user movement with Fitts law and regression alone. However, regression statistics are still informative and could be used differently to help adapt the system to the user when used alongside other statistics including hits, meanMT, and descriptive statistics.

Participants were largely positive about the usability of TAGER, particularly the use of the VR headset, they felt that it had a considerable impact on their enjoyment and performance using TAGER. User profile results comparing the VR headset to the PC monitor showed the VR headset produced a better movement performance from the upper limb impaired participants, with faster and more improved accuracy of their movement. However, the VR headset does seem to increase the occasions of overshooting the target, but this would be considered an improvement since all users significantly decreased their time outs and hand loses. Occasional occlusion of the targets by the user’s real hand was an issue that frustrated users. A benefit with the VR headset is that it does not suffer from occlusion from the user’s real hands unlike the PC monitor did when the participants were reaching towards the PC monitor. This is because the display is inside the VR headset fixed on the eyes. A common frustration for participants was the difficulty in acquiring the origin object, which required more effort by the user which could have contributed to the level of fatigue seen by some of the participants. The length of the experiment was also an issue it took too long for participants to complete the experiment which did cause three out of eight of the participants to quit the experiment prematurely. Motivation to play TAGER for those three participants may have been hugely impacted due to the considerable time since any of the participants had received any regular rehabilitation. Although this experiment was designed to obtain enough data to evaluate TAGER’s usability and user modelling, it would be advisable that future systems be more flexible in the time spent using the system for upper limb impaired users. It is possible with future developments, TAGER could use the user's profile to identify movement behaviours and give users intelligent feedback and guidance of their movements and when the user should stop playing to rest helping to reduce fatigue.

Feedback and results of the participants showed that additional modifications to TAGER are required to improve the rehabilitation qualities for improving motor control. Changes should provide a more fun and immersive experience this would suggest the gamification of the TAGER system. To provide a more fun and enjoyable rehabilitation experience, it would be recommended to add a game or a series of games that incorporate rehabilitation exercises to motivate patients to adhere to their rehabilitation exercises. The continuous wearing of the VR Headset enhances the viewing experience for additional improvements in immersion, motor control, and eliminate occlusion from the real-world hands, and the time to complete the task should be reduced as much as possible. These changes will reduce the boredom and frustration seen by some of the users thus encouraging them to continue to engage with the system more often. It is also possible that because of the lower number of participants recruited for this study, results may not have fully highlighted the limitations of upper limb impaired user movements, and it is expected that with a larger group of participants recruited it may strengthen the results as well as produce other interesting results not seen in the current findings.

# 6.7 CONCLUSION

An improved TAGER system was used with upper limb impaired participants following a stroke. TAGER was used to evaluate Fitts Law for its suitability to model upper limb impaired user movement using the novel natural user interface device, the Leap Motion Controller for the design of a personalised and adaptive rehabilitation system. Comparisons between able-bodied from the previous study and impaired participants were also analysed. Results showed that it was possible for upper limb impaired users to model movement performance. This showed similar results from the able-bodied experiment, identifying the effects of learning and fatigue. However, in some cases, it was difficult to model users through regression for adaptation, but the statistics from the regression were still informative by showing the level of predictability of the users' movement and how difficult the user was finding the tasks. In future systems when regression statistics are unreliable, it would be more appropriate to use regression statistics along with other statistics from the user profile to adapt differently. It should be suggested that design improvement would include the design of games into the rehabilitation system to provide a more enjoyable rehabilitation experience for the user and be flexible in the amount of time spent in the VR rehabilitation.

# 7 RESTEM: A VIRTUAL REALITY AND GAMING REHABILITATION SYSTEM

## 7.1 OVERVIEW

This chapter discusses the design and development of a new VR gaming rehabilitation system based on results from TAGER to provide a more fun and engaging rehabilitation experience. Each rehabilitation feature and game is described, and the design and development of an adaptive system also discussed.

## 7.2 DESIGN REQUIREMENTS

In addition to the previous requirements gathered for a VR rehabilitation system, more PPI and interdisciplinary workshops and hospitals visits were carried out before the design of the next system (APPENDIX S & U). Table 7-1 below shows more requirements gathered towards an improved and more gamified VR stroke rehabilitation system.

**Table 7-1: List of system requirements gathered from PPI sessions and interdisciplinary workshops based on demonstrations of the current system.**

| Requirement Description | Type |
|---|---|
| A more detailed calibration is required to capture more of the user's movement capabilities | Rehab Specific |
| Performance feedback needs to be included to show the user how well their rehabilitation is going | Rehab Specific |
| Introduce the use of the users both hands | Rehab Specific |
| Have the possibility for interaction along the table for users that can't elevate their arm or use the table for resting. | Rehab Specific |

| | |
|---|---|
| Having a competitive social feature may encourage increased engagement | Game Specific |
| The system should be more enjoyable; game elements should be added to entertain and motivate the user to engage in their rehabilitation. | Game Specific |
| The system should include a range of games with varied gameplay. | Game Specific |
| There should be a place for the patient to relax between games, and to review game and rehabilitation performance. | Game Specific |
| The system should incorporate difficulty adaptation to personalise the tasks to individual participants | Game Specific |

# 7.3 ARCHITECTURE

## 7.3.1 SYSTEM HARDWARE

For the final experiment the system architecture, hardware and drivers were modified, and a new system created called RESTEM, which in this context is a metaphor to re-growing motor function. Changes included the addition of the commercial release of the Oculus and upgrading to the latest Leap Motion SDK. The Kinect and Myo sensors were excluded from this new version of the system to minimise the sensors required and increase usability. The Kinect was mainly excluded from the experiment due to the lengthy setup time it took in the previous experiments and the considerable space that the device occupied. The Myo armband’s short battery life, difficult calibration process and inaccurate sensor reading of users with low arm muscle density were the reason for its exclusion. Another reason to exclude the sensors in this experiment was to investigate RESTEM’s capability to adapt the level of difficulty of the games over-time, only the important interaction devices would be required to do this. A range of games was added to the system to help test the user model and to investigate the impact of games on engagement. Included are three games; Fetch, Cannon Grab, Knights Run. RESTEM implements the following hardware technologies:

*Leap Motion Controller (Leap Motion, USA)* – is a small compact infrared depth-sensing camera specifically for hand and finger detection. Details are explained more on this device in previous sections (4.3.1). Since the previous experiments, the Leap Motion Controller has been updated their software that improves hand detection, increasing accuracy and precision. The new and improved interaction engine provided better gesture recognition and more natural hand interaction. Participants use the Leap Motion Controller in RESTEM as the main method of motion tracking and interaction with RESTEM's VR environment to facilitate the reaching and touching of the target objects.

*Oculus CV1 (Facebook, USA)* – in the previous studies the Oculus DK1 prototype was used, since then Oculus released a commercial version of the Oculus and works similarly by using a 7" OLED screen placed inside the headset. Table 7-2 shows a comparison of the prototype (Oculus DK1) and the commercial version (Oculus CV1) and minimum PC specification. Two identical images are projected side by side on to this screen, one for each eye. Each of these images has a resolution of 1080x1200 (4:5 aspect ratio). Within the headset, two lenses, one for each user's eye, that focus and reshape left and right images on to each eye to create stereoscopic 3D images. The commercial version used a new constellation system design, was two small external infrared cameras are placed on a desk to improve tracking of the user's head position and orientation. The system was upgraded to the Oculus CV1 (Figure 7-1) to increase immersion in the VEs. Its design was improved so that it was now easier to wear, hardware and drivers were more reliable, software more responsive, and included integrated headphones. It was expected that these improvements would help retain the user's motivation, providing a more enjoyable experience while also supporting improved user movement performance.

**Figure 7-1: The latest version of Facebook's VR headset, the Oculus CV1**

**Table 7-2: A Comparison between the different versions of the VR headsets**

| Oculus CV1 - Minimum Specification | | |
|---|---|---|
| Graphics | NVIDIA GTX 960/ AMD Radeon R9 290 | |
| CPU | Intel i3-6100/AMD Ryzen 3 1200, FX4350 | |
| Memory | 8GB RAM | |
| OS | Windows 10 | |
| Feature | Oculus DK1 | Oculus CV1 |
| Display (per eye) | LCD, 640×800 | OLED, 1080x1200 |
| Built Audio | No | Yes |
| Connectivity | HDMI, USB 3.0 | HDMI, USB 3.0, USB 2.0x2 |
| Weight | 380g | 470g |
| Field of view | 110 | 110 |
| Latency | 50ms-60ms | 20ms |
| Refresh rate | 60Hz | 90Hz |
| Power | Main power | USB Powered |

### 7.3.2 SOFTWARE TOOLS

The software tools used to develop RESTEM were similar to TAGER. The Unity game engine was used, Unity (version 2017.3) is a 3D and 2D cross-platform game engine for designing and developing VEs and games for the major platforms such as Windows, Mac, modern game consoles and mobile devices. RESTEM was developed and written in C# using the Microsoft Visual Studio development environment. Unity is a popular game engine among the community of game developers at many levels. Its popularity is mainly due to the large community of support, excellent documentation, and game asset support from hardware manufacturers has been very helpful for the rapid integration of the Leap Motion Controller and Oculus CV1 into RESTEM.

### 7.3.3 A PERSONALISED & ADAPTIVE SYSTEM

At the core of RESTEM is APPRAISER (Figure 7-2), which personalise rehabilitation based on physiotherapy and occupational requirements and adapts the user’s motor function using intelligent software to enhance engagement in the recovery process. APPRAISER defines user profiles in real-time and refined over repeated use, which provides tailored physical rehabilitation sessions for each person. It would be expected that a physiotherapist or occupational therapy including carers would be involved in the initial setup of the rehabilitation system at home to ensure a safe and comfortable environment for the stroke survivor and for carers to be trained on how to use the technology safely with stroke patients on a daily basis. Below is a description of the proposed operations of APPRAISER to be used in RESTEM.

Personalise

1. *VR Hardware and Environment installation* - VR setup for specific environments (home, hospital, community).
2. *Impairment Configuration* - Manual input information required about the user’s impairment, e.g. upper limb capability, cognitive impairment, or visual problems.
3. *Physiotherapy Requirements* - RESTEM’s rehabilitation exercises resemble physiotherapy exercises based on advice from clinicians.

4. *Induction* - Initial stages of the calibration in RESTEM includes a brief induction to the technology
5. *Initial Motion Calibration* - The Calibration phase auto-configures users range of motion, holding strength and reaction time through fun interactions (see 8.2.6.2 for more)

Adapts

6. *Motion Calibration* – Though an initial calibration is performed during setup, calibration is required at the beginning of each session to account for improvement or deterioration in upper limb function this can happen, for example, the person may be tired or in pain that day.
7. *Activity configuration* – based on the “impaired configuration” a tailored set of rehabilitation games are selected that are suitable for the patients. RESTEM currently does not include this for experimental purposes but has been flexibly designed to include this operation in the future.
8. *Interaction* – games are calibrated based on user profiles and the motion calibration. The game interaction space is adjusted according to the Range of motion calibration, and difficulty of the interactions are set from the user's profile.
9. *Feedback* – RESTEM makes use of knowledge of results and knowledge of performance feedback. The games use design best-practices to provide information about success and failure during and after the games as knowledge of results. Knowledge of performance provides users with feedback on the quality of their movement after each game through SAC (see section 7.3.4 for more detail). Visual and audio feedback are given to the users in-game by means of proximity colour changes, shadowing, and sound effects on completion of reaching and touching an object.
10. *Profile monitoring & Recalibration* – each session might be considered as a closed loop control system, in that the system is responsive to the user’s performance based on the user’s profile. The user profile is obtained multiple times and in real-time during the interactive sessions including movement capability, playability, and mood/fatigue. The information is fed into the adaptive algorithms implemented into RESTEM to recalibrate the games’ task difficulty for the next set of rehabilitation exercises.

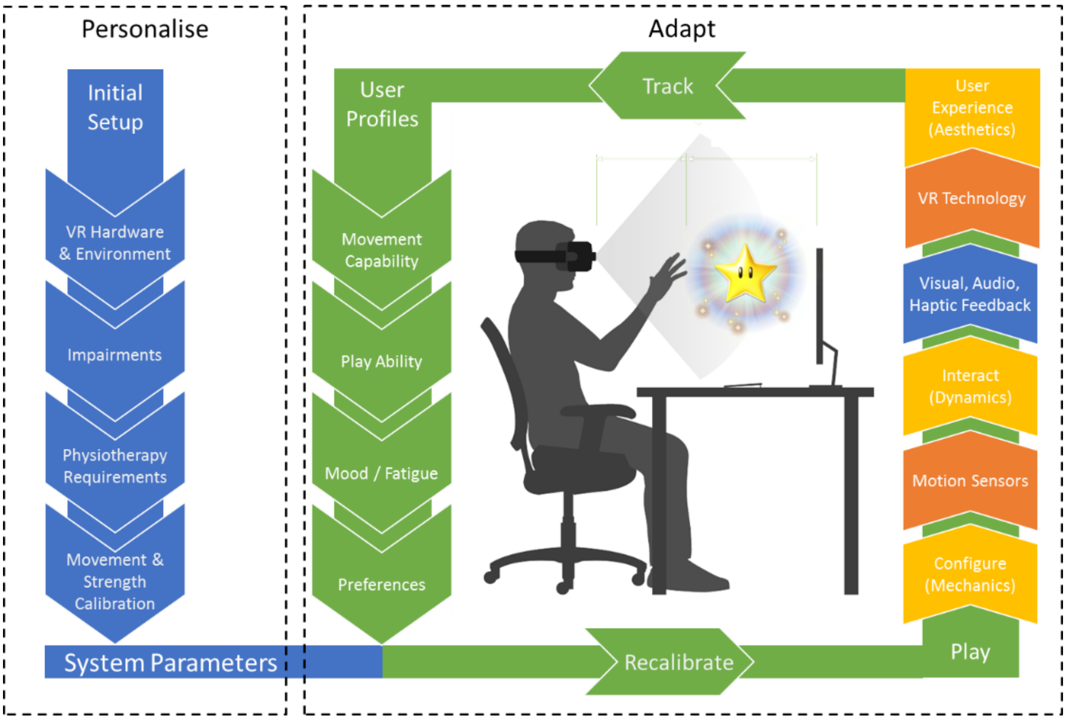



**Figure 7-2: APPRAISER personalised rehabilitation system**

### 7.3.3.1 ADAPTIVE DIFFICULTY ADJUSTMENT

Determine the task difficulty from the user's profile focuses mainly on the use of the analysis of the Linear Regression of Fitts Law. Fitts Law states that the time required to reach and touch an object is dependent on the sizes of the object and how far away it is from the user. Others have proposed variations on Fitts Law to improve or adapt it to different situations. In RESTEM, Murata's version of Fitts Law is used, that accounts for 3D spaces by including a directional parameter to the object to quantify the difficulty of the task more precisely in 3D space (see chapter 2.3.1.3 for more information). The results of the linear regression make up the majority of the user profile along with descriptive statistics of the residuals of the regression and target acquisition statistics explained more in section 7.3.5.

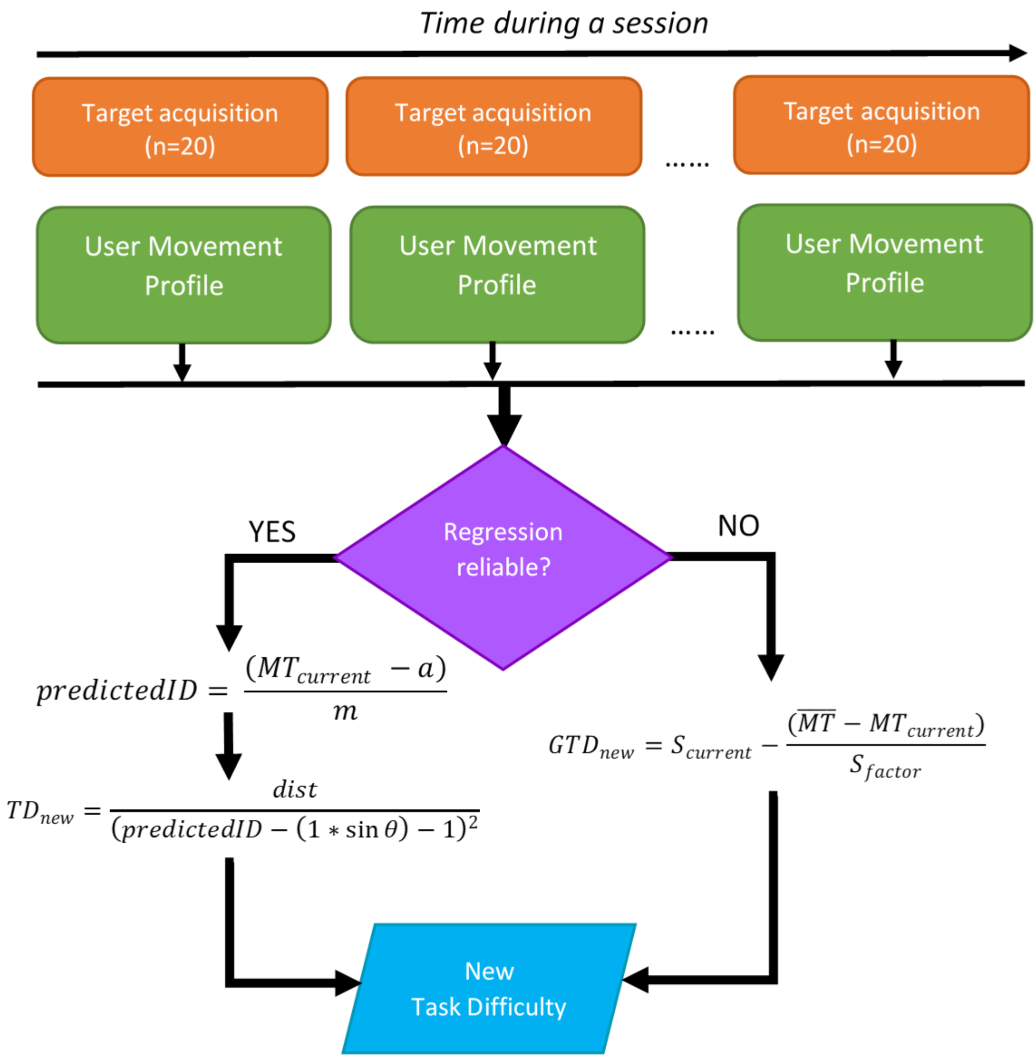



**Figure 7-3: High-level view of the adaptive difficulty adjustment approach**

From the findings in the previous experiment, it was recognised that using the regression line from Fitts Law to automatically adapt the difficulty of tasks is more successful once the user has gained competency with the natural user interface within VR. Before this, the statistics gained from regression can be used along with other statistics from the user movement profile to ensure continuous adaptation to provide users with a challenge level that equates to their skill level. Figure 7-3, shows a high-level view on how RESTEM adapts the difficulty of the tasks based on the user's profile. During a session, multiple user profiles can be generated to account for changes in user condition. A user profile is created each time when the user has completed 20 reach and touch tasks, the profile is then analysed, and the regression model is examined to determine its reliability. The regression model is said to be reliable when the $R^2$ value is above a certain threshold; the threshold is based on the results from the previous experiment with able-bodied participants using the mean $R^2$ of all users. A regression model was considered reliable if $R^2$ was above 0.200/1.0 explaining more than 20% of the user's movement variation. Adaptive difficult adjustment in RESTEM includes altering the size of the target object that the user has to reach and touch. The adaptation approach used by RESTEM depends on the reliability of the regression. For a reliable model, the regression line is used to find the $predictedID$ from the current user profile using equation 7-7, where $MT_{current}$ is the current movement time last recorded by the user, $a$ and $m$ is the y-intercept and regression line gradient of the regression line. Once $predictedID$ is found the value is used in equation 7-8 to determine the new task difficulty ( $TD_{new}$ ), where $dist$ is the distance to the next target, $predictedID$ is the result from equation 7-7, and $\sin\theta$ is the angle towards the next target. For unreliable regression results from the user profile, equation 7-9 is used to provide a basic approach to adapting the scale of objects but remained relevant to the user's movement. Equation 7-9, calculates the task difficulty ($GTD_{new}$), where $S_{current}$ is the current object size used, $\overline{MT}$ is the mean movement time, $MT_{current}$ is the movement time last recorded by the user, and $S_{factor}$ is the value to scale the result to the appropriate unit of scale for the game engine. This value is set at 10 for use with the Unity game engine. Once the task difficulty has been calculated this is used to adjust the target object's size until the user movement profile has been recalculated and a new object volume is determined.

$$predictedID = \frac{(MT_{current} - a)}{m} \qquad (7\text{-}7)$$

$$TD_{new} = \frac{dist}{(predictedID - (1 * \sin\theta) - 1)^2} \qquad (7\text{-}8)$$

$$GTD_{new} = S_{current} - \frac{(\overline{MT} - MT_{current})}{S_{factor}} \qquad (7\text{-}9)$$

### 7.3.4 PERFORMANCE FEEDBACK

Feedback on user actions in games is an important factor to keep the user engaged and providing meaningful gameplay. For stroke patients, feedback from physiotherapists and occupational therapist on their performance to perform rehabilitation exercises is also important for motivation. In all the VR games, knowledge of results is provided, this is feedback concerned with how successful a rehabilitation exercise was performed, the feedback is different between the VR games. The knowledge of results feedback is explained in more detail for each game later in the chapter. In RESTEM, a feedback mechanism is proposed for providing knowledge of performance to the user on his/her movement performance of the reaching and touching tasks. Knowledge of performance is feedback related to the quality of the rehabilitation exercise performed such as trunk range of movement, or hand trajectories (Deutsch Judith E, 2013). The aim is to investigate how easy it is for users to understand the knowledge of performance information represented as a line graph with three values of performance plotted for each session the user has completed (Figure 7-4). The three performance values are Speed, Accuracy and Consistency (SAC) and are explained how they are derived from the user's movement profile below:

1. *Speed*- measures how faster the users were at performing the reaching and touching tasks. The values used to determine speed depend on the reliability of the regression model using the same structure described in section 7.3.3.1. If the reliability of the regression is above an $R^2$ threshold, it is considered reliable, and the speed is calculated based on the skew of the residuals of the regression line. Skew explains the symmetry of the movement times, a positive value shows faster movement times more often, a negative skew shows slower movement times more often, and a zero value shows an equal distribution of fast and slow movements. Positive values show improvements in speed; negative values show a decline in speed. If regression is not reliable the speed is calculated using the mean movement time, a low value of movement time shows the user was faster and higher values shows slower movements. As mean movement time values have the opposite meaning from skew, e.g. high positive skew = fast movement & high mean movement = slow movement, the values of mean movement time are inverted to give the same meaning. To calculate speed, equation 7-12 is used, where $x$ is skew or mean movement time from the user's previous six user movement profiles, $w$ is the number of user profiles used (w=6) per game, $\left(\frac{x_i - x_{min}}{x_{max} - x_{min}}\right)$ is each x value normalised between 0 and 1.

2. *Accuracy* – measures the precision and control the user has of their movements during the tasks. To calculate accuracy, the same equation (7-12) for calculating speed is used. However, different values are used to represent accuracy. For a reliable regression model, kurtosis from the user movement profiles calculate in each game (n=6) is used. Kurtosis explains the weight of the tails of a distribution known as outliers. High positive values indicate occasional high movement times; a low negative value shows there were nearly as many high movement time values as low movement time recorded by the user. A value close to zero shows a normal distribution showing a consistent accuracy. Negative kurtosis represents bad accuracy, positive values state good accuracy more often and zero shows excellent accuracy. However, it is expected that a zero kurtosis would be hard to obtain due to the unpredictably of human movement. If a non-reliable user profile is discovered, then the overshoots statistic is used. The overshoot value is a number that shows how many targets the user has missed initially and had to readjust their movement to acquire the target; larger values show inaccuracy by the user, which has the opposite meaning to kurtosis, so the values of the overshoot statistic are inverted to give them the same meaning.
3. Consistency - is the correlation between the speed and accuracy of the user's movements. The statistical correlation method was used (equation 7-10) to compare a series of speed and accuracy values (n=6) during each game to determine the direction of correlation. Results lie between 1 and -1, a value greater than zero states that the user's speed and accuracy are improving together, a value less than zero states that the performance is declining in both speed and accuracy, and zero value shows that the user's speed and accuracy are not consistent. The following formulas were used to calculate consistency, where $r_{xy}$ is the correlation result, $(x_i - \bar{x})$ is each value of speed minus the mean of the speed value and $(y_i - \bar{y})$ is each value of accuracy minus the mean of accuracy.


**Figure 7-4: A screenshot of the SAC line graph in RESTEM's VR living room**

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{7-10}$$

$$y = \frac{\sum_{i=1-w}^{n}\left(\frac{x_i - x_{min}}{x_{max} - x_{min}}\right)}{w} \tag{7-11}$$

## 7.3.5 DATA COLLECTION AND STORAGE

In this experiment, game and movement performance statistics on the user's target acquisitions are collected. On each complete target acquisition, the Fitts Law and other movement information were obtained and stored in a comma separated value (.csv) file under the participant's username obtained from a login screen, e.g. 3001_Fitts.csv. The complete list of data statistics is listed in Table 7-3. Once the user has completed 20 target acquisitions, RESTEM calculates a user movement profile using the method described in section 7.3.3.1, linear regression performed on the previous 20 entries stored in the users Fitts.csv file. The “Basic C# Statistics” library provided by Microsoft was used to perform linear regression along with the other descriptive statistics of the residuals of the regression line, values include standard deviation, kurtosis and skew. A full list of the user movement profile data is seen in Table 7-3. For each session, the participant movement profile is calculated 18 times ready to be used each time to adapt the difficulty of the tasks and stored in a CSV file called <username>_ProfileAnalysis.csv. Discussed earlier in the “Performance Feedback” section above to provide the participant with high-level information (SAC) that is easily understandable to the participant about their movement performance in the VR games. SAC is calculated using user’s movement profile and is also stored in a .csv file under <username>_OverallPerformance.csv and in an extendable markup language (XML) file that holds information of all users explained more in the next paragraph.

**Table 7-3: List of data statistics stored in the relevant CSV files**

| Data statistic | Description |
|---|---|
| Fitts.csv | |
| Movement Time | The time taken to complete each reach and touch task |
| Index of Difficulty | The difficulty of the task |
| sin angle to target | The angle from the origin to target |
| Origin position | Collision position when the user hit the origin object |
| Target position | Collision position when the user hit the target object |
| Status | Determines if the user overshot the target or lost visibility of their hand |
| ProfileAnalysis.csv | |
| Standard Deviation | How spread out the movement times are from the regression line |
| Kurtosis | Detection of outliers (overshooting and hand lose indicator) |
| Skew | The symmetry of the movement time along the regression line |
| R-Squared | A measure of how close the data is to the fitted regression line showing how predictable the user's movements are during the tasks. |
| Gradient | The steepness of the regression line |
| Y-intercept | Where the line crosses the y-axis (potentially reaction time indicator) |
| Hits | Number of successful hits (without overshooting or losing their hand) |
| Misses | Number of failed attempts to select the target |
| Overshoots | Missed the target but acquired after trajectory adjustment |
| MeanMT | Mean movement time of the 20 target acquisitions |
| PredictedID | Predicted ID to determine the new object’s volume, calculated using equation 8-1 |
| Current MT | Last movement time recorded by the user |
| New level of difficulty | The new difficulty level the user will experience in the next task |
| OverallPerformance.csv | |
| Speed | How fast the user was from the task in each game |
| Accuracy | How precise the user’s movements were in each game |
| Consistency | Consistency in both accuracy and speed |

The XML file holds all necessary information that RESTEM needs to profile and adapt to the user as well as general demographic information. Information includes the previous user’s movement profile, the current difficulty calculated from the user’s movement profile, login details, and the hand the participant will use to complete the tasks. A detailed list of the data stored for each user in the XML file is seen in Table 7-4. As soon as the participant logs into RESTEM, the XML is read once, gathering storing in memory the necessary information about the current logged in user. This saves memory and processing power compared to reading XML file only when it is needed which requires memory allocation updates and more processing power that isn’t necessary. During play, RESTEM updates the XML data obtained at login when the user's profile, game scores and level of difficulty has changed. Any updates are saved when the user has exited the games.

**Table 7-4: List of data statistics stored in the relevant XML files**

| XML File | |
|---|---|
| Data statistic | Description |
| Username | Username to login |
| Password | Password for login |
| Session No. | Current play session the user is in |
| Hand used | Hand the user will use |
| Total Cannon Grab score | The total score of the cannon grab games overall sessions |
| Total Knights Run score | The total score of the cannon grab games overall sessions |
| SAC list | List contains each SAC value recorded at the end of each session |
| The current user movement profile | List of movement profile information from Table 7-3 in the ProfileAnalysis.csv file |
| The current level of difficulty | The object volume RESTEM for difficulty adaptation |

## 7.3.6 RESTEM USER INTERFACE DESIGN

A redesign of TAGER was necessary to evolve the design towards a complete system that an upper limb impaired user may find more acceptable for self-managed rehabilitation in a clinic or at home. The redesigned system was called RESTEM and includes a simple login screen for user identification and security, a fun calibration process for motor skill assessment, a virtual living room to provide a relaxing place for the user to review progress and navigate through games, and currently includes three rehabilitation games. Below describes RESTEM in more detail the general flow that a user would experience during interaction with RESTEM experiment.

### 7.3.6.1 LOGIN

When a person launches the RESTEM application, they are asked to log in with a username and password given to them by the investigator on the day. The user is then asked to select which arm is impaired through a checkbox functionality, only once in the first session. This information enables the system to search for the user's information stored locally on the computer and allows the system to update the user's status such as score, progress, performance and adaptive attributes for the VEs and games. If it is the first time a user has logged in, the system automatically creates a new user profile for them, so they can log in next time and update their attributes.

### 7.3.6.2 CALIBRATION

From the previous studies, it was found that to be more inclusive of a diverse range of upper limb motor skills, a system should provide a calibration for the modelling and assessment of each user's initial movement capabilities. Calibration also helps introduce the user to the novel technologies by performing kinematic actions and acts in part as a training session. Through a series of movement and strength calibration tests a user's capability is profiled. This profile is then used to adjust the VEs and Games and provide an easily accessible and personalised experience for individuals. The calibration scene begins in a science fictional training environment, with an animated robot called "Reebo" (Figure 7-5) who introduces the user to the system and guides the user through the calibration giving meaningful feedback in a fun and comedic way.

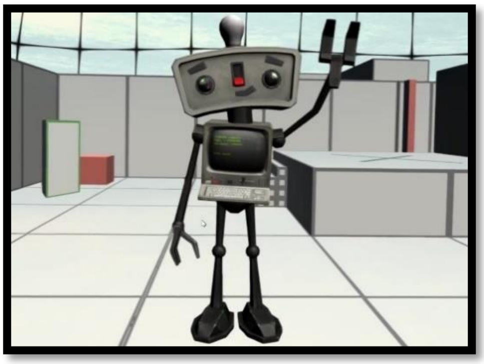


**Figure 7-5: Reebo, a screenshot the participant's virtual instructor for the calibration**

The calibration process (Table 7-5) is used by the user every time they log into RESTEM to assess if their capability has changed. The below list explains in more detail the order of the calibration process and the user's actions from Table 7-5.

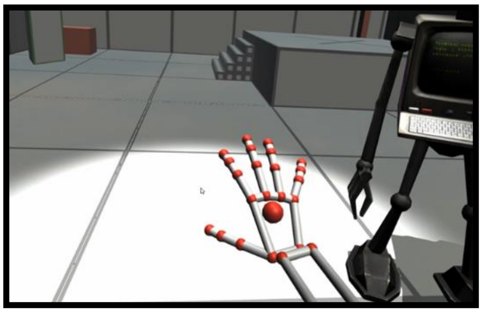
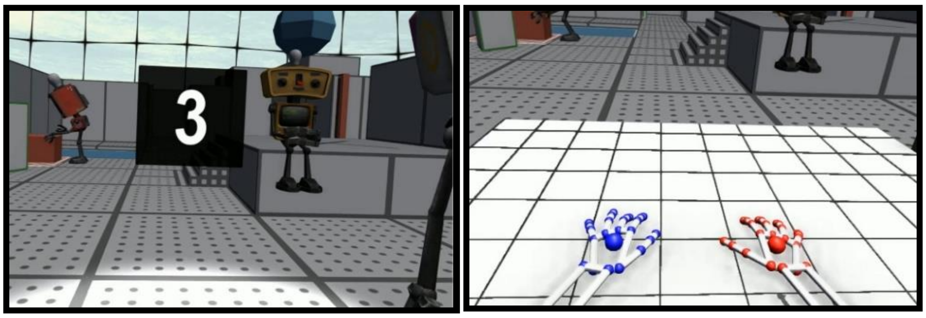
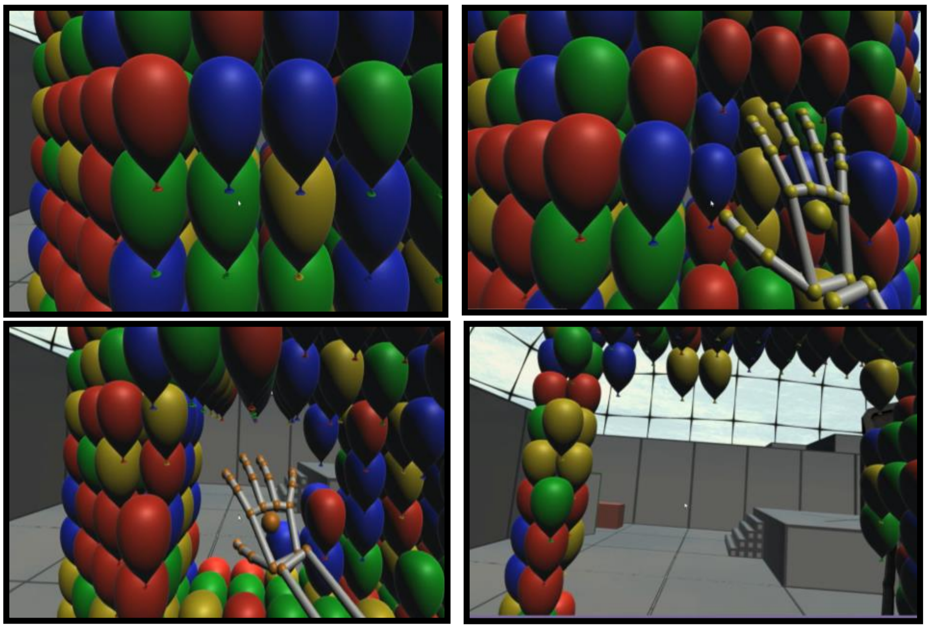
1. *See your hands* – the Leap Motion Controller is mounted on the VR headset, and so when Reebo asks the user to look down towards their real hands, the Leap Motion Controller will detect their hands and show a virtual version of their hands within VR, and the stage starts.
2. *Find the table* – next the user is asked to place their real hands on the real table in front of them. The virtual hands are then accurately positioned where the real table is. While their hands are still resting on the real table, a 10-second timer counts down then a virtual table is generated to locate the position of the real table surface. Knowing where the real-world table is in the virtual environment enables RESTEM to provide interactions on a flat surface to include users even if they cannot elevate their arm against gravity.
3. *Range of Movement (RoM)* – this is considered to be the most important aspect of calibration because it provides important information about the extent of the user's impaired upper limbs movement capability. It defines a personalised RoM space in which user interactions will reside. To capture the user's RoM a feature was designed that uses the tracking space attributes of the Leap Motion Controller. A volume of space is calculated in the shape of a cone, the volume of space is then divided into many quadrates. An interactable game object is placed inside within

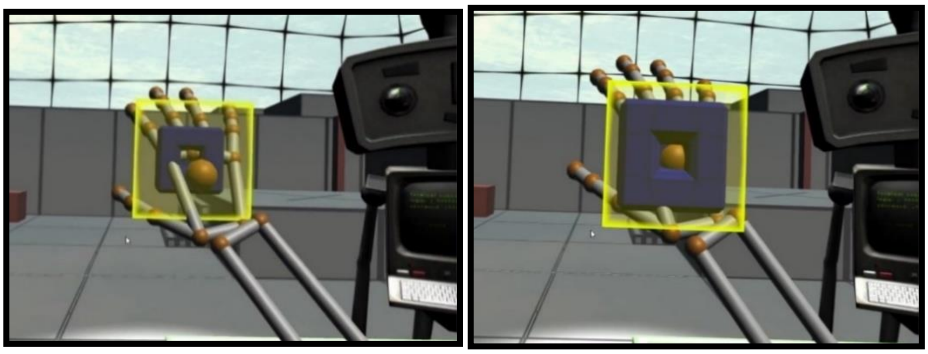
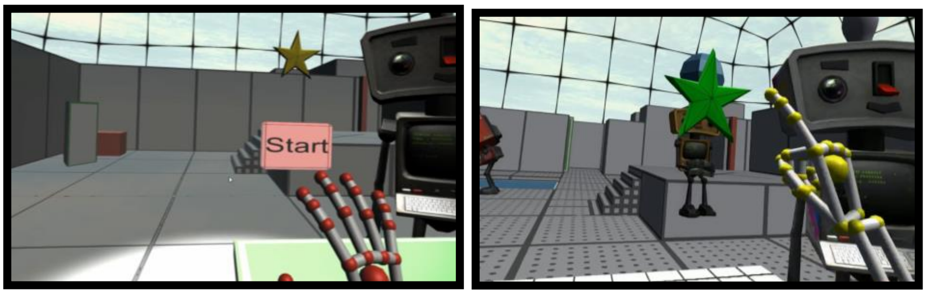
each quadrate of this cone shape – for calibration balloon objects are used. The user uses their hands to hit and pop all balloon objects that they can physically reach. When completed the system automatically calculates the volume of the empty space left by the popped balloons and is used to personalise movement extent within the system for each user (Table 7-5). This new RoM space is used throughout the RESTEM system for placing interactable menus inside and to place interact game objects for manipulation in gameplay and Fitts Law use.

4. *Hold strength* –was designed to find how long a user can hold and lift their arm against gravity, which could be a useful measure for the endurance of the user's arm for interaction purposes. This measure was measured using an inner box and an outer box. The boxes appear within the user RoM boundary calculated previously, the inner box is placed inside the outer box seen in Table 7-5. The user is asked to move their hand inside the inner box. Once inside the inner box begins to gradually scale toward the size of the outer box. The user holds their hand for as long as possible or until the inner box scales to the same size as the outer box. When the user has removed their hand, either because they couldn’t hold their arm any long or the maximum scale is reached, RESTEM stores the time that the user could hold their arm. This task is performed three times, and an average is calculated for that user and stored at the end of the exercise. The average is then used for 3D features similar to hold and press button functionality on 2D touchscreens.
5. *Reaction time* – was to measure how quickly each user could react to certain stimuli. This might be useful to compare linear regression coefficients against reaction time to determine if this impacts the quality of fit of the regression line. Reaction time was calculated to use a method of reacting to a change in an object. The user is shown a “Start” button and a small “star” shape, they are asked by Reebo to click the “Start” button and waits until the star changes colour and size (changes randomly between 3 and 10 seconds). As soon as they see this change, they click the “star” shape as fast as they can. Reaction time is stored,

and the objects are reset, and the process is repeated three times with an average calculated at the end of the exercise.

**Table 7-5: The calibration process order and screenshots of each stage of the process**

| Order | Screenshots |
|---|---|
| See your hands |  |
| Find the table |   |
| Range of Movement (RoM) |  |

| | |
|---|---|
| Hold strength |  |
| Reaction time |   |

## 7.3.6.3 VIRTUAL LIVING ROOM

The Virtual Living Room is much like any main menu seen in the majority games; it acts as a location that the user is always returned to after playing. It is a place where a user can navigate anywhere throughout RESTEM, with multiple menus and information such as achievements, games, and other user statistics. This is like the Oculus Home environment that begins by placing the user within the living room of a house or outside in a garden where they can navigate to games from a floating menu. Much like the Oculus Home, the Virtual Living Room places the user inside a relaxing and interesting living room space as though they are sitting on a sofa watching TV (Figure 7-6). There is a range of purposes for using the Virtual Living Room as a central location for the users to return to after playing the VR and gaming experiences, see below.

1. *Relaxation* – it is common that users with impaired upper limbs may suffer fatigue after their traditional rehabilitation exercises. The rehabilitation games and VR experiences in RESTEM can also affect user fatigue. It is important that the user has a place to relax at any time, rather than continuously performing their rehabilitation to reduce fatigue. A living room was chosen because it is a common room that users tend to relax in when at home.

2. *Leaderboard* – the Virtual Living Room contains a leaderboard that shows the top 10 highest scoring players and their position on the leaderboard. The scores are an accumulation of all the user's game scores throughout time playing. A leaderboard is a common gamification mechanism and encourages competition between users, providing social status and incentive for the user to continue to play.
3. *Performance display* – this display shows measures of user performance over-time. The display shows a line graph depicting the user's SAC over multiple sessions, described in section 7.3.4 for more detail. The display shows other statistics such as the number of hits, misses and overshoots of the games. The calculations of SAC were to give a high level and simplified view of the user's movement performance; thus, SAC was derived from values of the user's profiles to motivate users to improve in their rehabilitation exercises.

**A** **B**

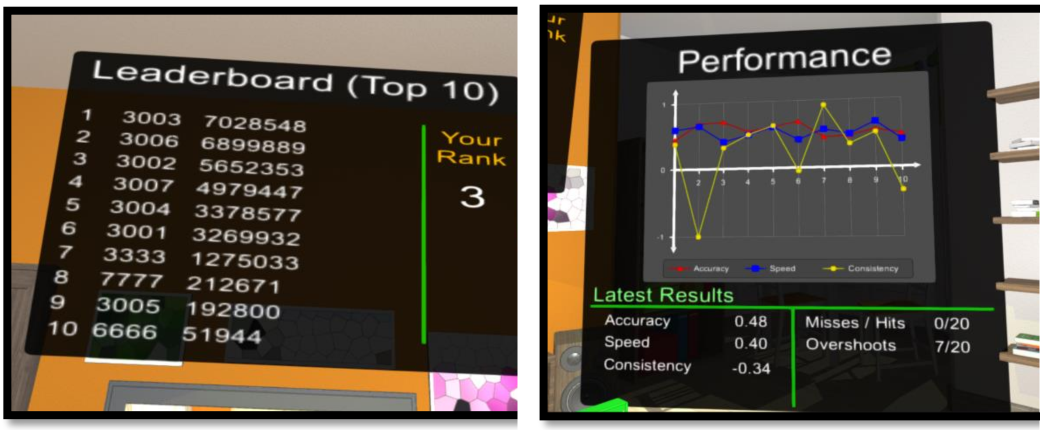



**Figure 7-6: Screenshots of the menu displays inside the Virtual Living Room (A: Leaderboard, B: SAC performance chart)**

## 7.3.7 VR GAMES

Below describe the games included in RESTEM and discuss the gameplay design of each game including the mechanics, dynamics, and aesthetics. Mechanics explain the rules and interaction within the games, dynamics display the outcome of the interaction with the mechanics and the potential aesthetics describing the emotional response invoked by the dynamics of the game (Hunicke, Robin; LeBlanc, Marc; Zubek, 2004).

### 7.3.7.1 FETCH

Fetch is a VR experience that encourages the user to play with a virtual dog in a virtual garden and enjoy the company of their virtual pet. The design mechanics of Fetch places the user in the virtual garden and is asked to play fetch with the dog by using their virtual hands to pick a tennis ball from the 3D space in front of them. The balls are placed inside the RoM space quadrates discussed earlier in the calibration section, this task focuses on reach and touch exercises for rehabilitation (Figure 7-7). RESTEM makes use of Unity's integrated physic engine (PhysX) to detect collisions between the hands and the tennis balls automatically. The collisions are only detected by the movement of the user's most impaired hand, ascertained from the profile determined at login. The dynamics of Fetch shows when the user collides with the tennis ball; the tennis ball attaches to the hand. To throw the ball, the user performs a pinching gesture; this applies a force on the direction the hand is facing. The dog uses pathfinding algorithms to intelligently navigate avoiding obstacles to fetch the ball and return the tennis ball to the user. The dog character is fully animated to run for and grab the tennis ball. The feedback in Fetch is limited, feedback on successful target acquisitions is shown to the user by the attaching of the tennis ball to the virtual hand and throwing the ball is seeing the ball being thrown in the air and the dog retrieving the ball. Feedback on failure is given to the user by the tennis ball failing to attach to the hand after attempting to reach and touch the target and failed pinch gesture performed by the user results in the ball not being thrown. Audio feedback is only given through the dog, barking to make the user aware that the dog has returned from retrieving the tennis ball. Fetch doesn't include a reward system for success or failure of actions or any goals to accomplish. It was intentional to give limited feedback to investigate the impact it has on the enjoyment of the games.

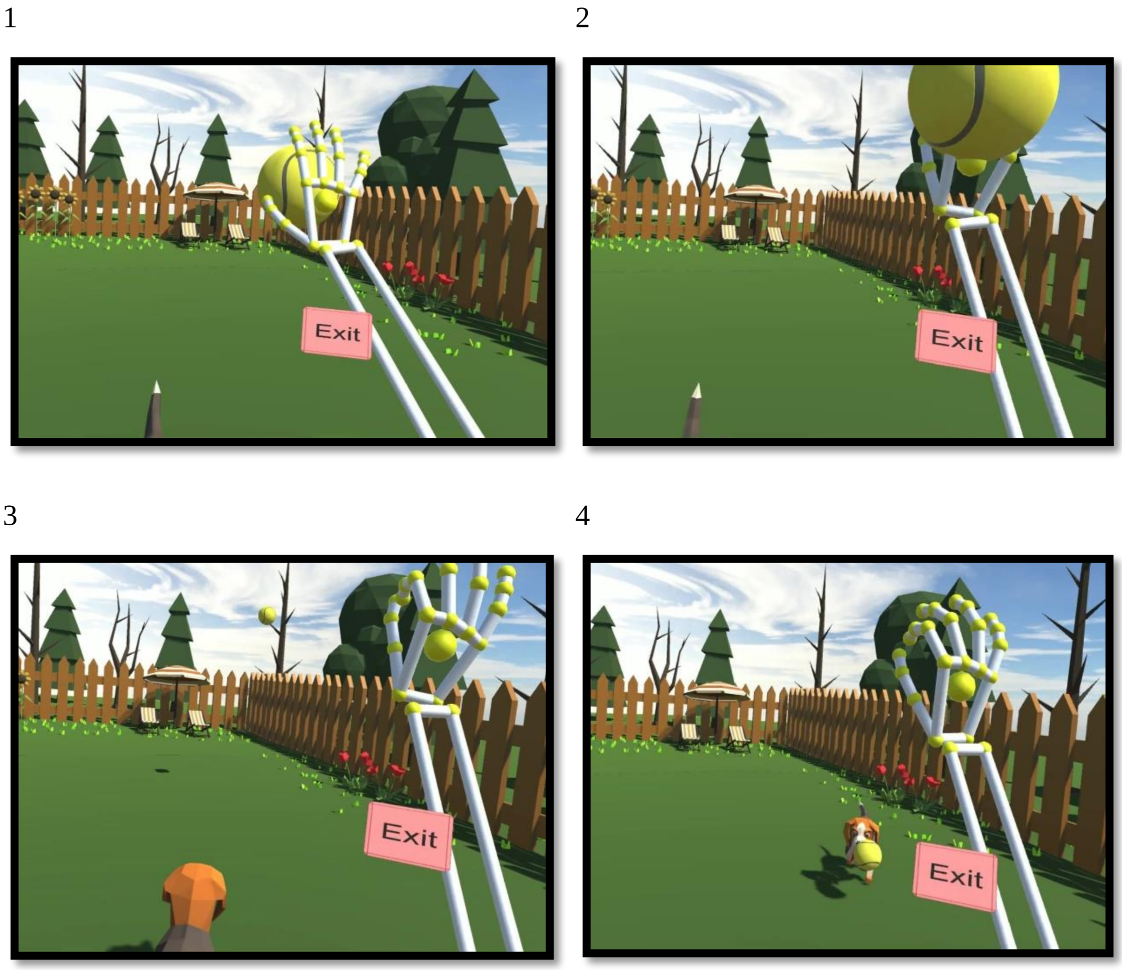



**Figure 7-7: Screenshots of the movement required to play Fetch, including the pinch gesture (3).**

Fetch also integrated other gestures using the Leap Motion Controller by giving the users the opportunity to command the dog to do tricks. This demonstrates the capabilities of the Leap Motion Controller to provide detailed hand/finger dexterity, which is potentially beneficial for focusing on rehabilitation exercises. The gestures are custom designed and are typical of rehabilitation exercises given to patients by physiotherapists. Table 7-6 shows the gestures that the user can use to command the dog to perform tricks.

**Table 7-6: List of hand gestures used to command the dog to do tricks**

| Gesture | Description | Dog action |
| --- | --- | --- |
| Supination | User rotate wrist from palm facing to palm facing up direction | Play Dead |
| Grasp | The user makes a fist, closing fingers towards the palm | Jump |
| Pinch | The user moves their index and thumb together while other fingers are closed | Sit |
| Thumbs Up | The user makes a fist shape but extends thumb out and upwards | Stand |

### 7.3.7.2 CANNON GRAB

The Cannon Grab game is based in a medieval setting surrounded by a castle and a medieval marketplace. The user is placed in front of five wooden barrels, and the mechanic's design in Cannon Grab get the user to grab cannon balls with their virtual hand from the air before they disappear, to score as many points as possible. Consecutive grabbing of cannon balls without missing any rewards the user with higher scores. Like Fetch, the cannonballs are placed randomly in each quadrate of the RoM space and appear one at a time. Grabbing cannon balls is similar to Fetch, attaching the cannon balls to the hand when on collision. However, once the cannonball has been grabbed, the game highlights the correct barrel to place it in by changing the barrel colour to green (Figure 7-8). Time limits are placed on the target objects once a cannonball appears a timer begins forcing the user to collide with the target before the time runs out and the cannonball disappears which places a time pressure on the user contributing to the dynamics of the game. The scoreboard is prominent in the game scene to encourage users to look at their score, which along with the time-sensitive cannon ball cause the user to experience a level of tension to score high points without missing any objects as fast as possible to climb the leaderboard. Feedback on target acquisition is provided visually and audibly to guide the user’s movement towards the cannonball, and proximity markers are shown. When the user is close enough to the cannonball, the colour intensity gets brighter the closer the user's virtual hand is the cannonball. Once the user has collided with the cannonball and attached to the hand, an appropriate success sound is heard, and a pop-up appears in front of the user to display the points he/she has earned. Placing the cannonball in the barrel another success sound is heard. Failure to hit a cannonball and release it in the barrel results in a negative sound and a pop-up appearing in front of the user notifying them of their missed chance. An accumulator reward system was implemented, consecutive grabbing of cannonballs without missing one, rewards higher points to the player to encourage the player to be more accurate with their movements. The addition of more feedback and a reward system in Cannon Grab compared to fetch, the reward for user actions give the user incentive and motivate the user to engage in rehabilitation exercises more.


**Figure 7-8: Screenshots of the Cannon Grab game and the interactions.**

### 7.3.7.3 KNIGHTS RUN

Knights Run is a game where players use their hand like a mouse cursor to navigate a player character, a medieval knight, around a 3D maze collecting mushrooms, gems to score the highest points possible. The player’s hand is held above the maze and close to the knight, and a target is projected on to the ground for the knight to follow (Figure 7-9). Interaction within the environment is context sensitive. For example, if a breakable wall is beneath the knight’s directional cursor, then the knight’s sword swinging animation begins (with particle and sound effects coming off the wall) and continues until the wall in broken (or the cursor is moved). Similarly, if the player encounters an enemy, they can attack and defeat the enemy in the same way. Attacking the enemies are optional but are encouraged as the more enemies killed by the player, the higher points are received using a multiplier/combination system, it is to encourage more interaction thus more exercise. Conflict with an enemy can inflict damage to the knight cause health to decrease if the player health reaches zero the knight dies and resets to the last checkpoint ready to continue again. This creates tension in the user to help the knight survive through the conflict and levels.  Points are also given to the user for exploration when they wander into new areas they discovered there is a series of collectables that reward points for exploring. Mushrooms items are placed along the trail to give the user points from traversing through the level. Feedback is given in both visual and audio, killing enemies should the knight swing his sword and yelling “die” towards the enemy, enemies close to the knight will “growl” and run towards the knight swing their axe. Once the enemies have died, the user is shown a pop-up that displays the point they earned. Collision with obstacles and collectables results in them disappearing with particles appearing, the appropriate sound heard, and a pop-up displays the points earned. When the user fails to keep the knight alive, an animation of the knight dying plays and the knight yells a dying sound. The main focus within this game is on coarse arm movement and arm strength in holding an arm in fixed locations (e.g. to attack an enemy), the amount of time to hold the arm in a fixed location is guided by the holding strength recorded from the calibration. This game would be considered the most complex of the three described above and may have required more cognitive abilities due to multiple gameplay features and mechanics. The primary aim for including Knight Run is to evaluate the complex features, usability and reliability before using it with upper limb impaired users.

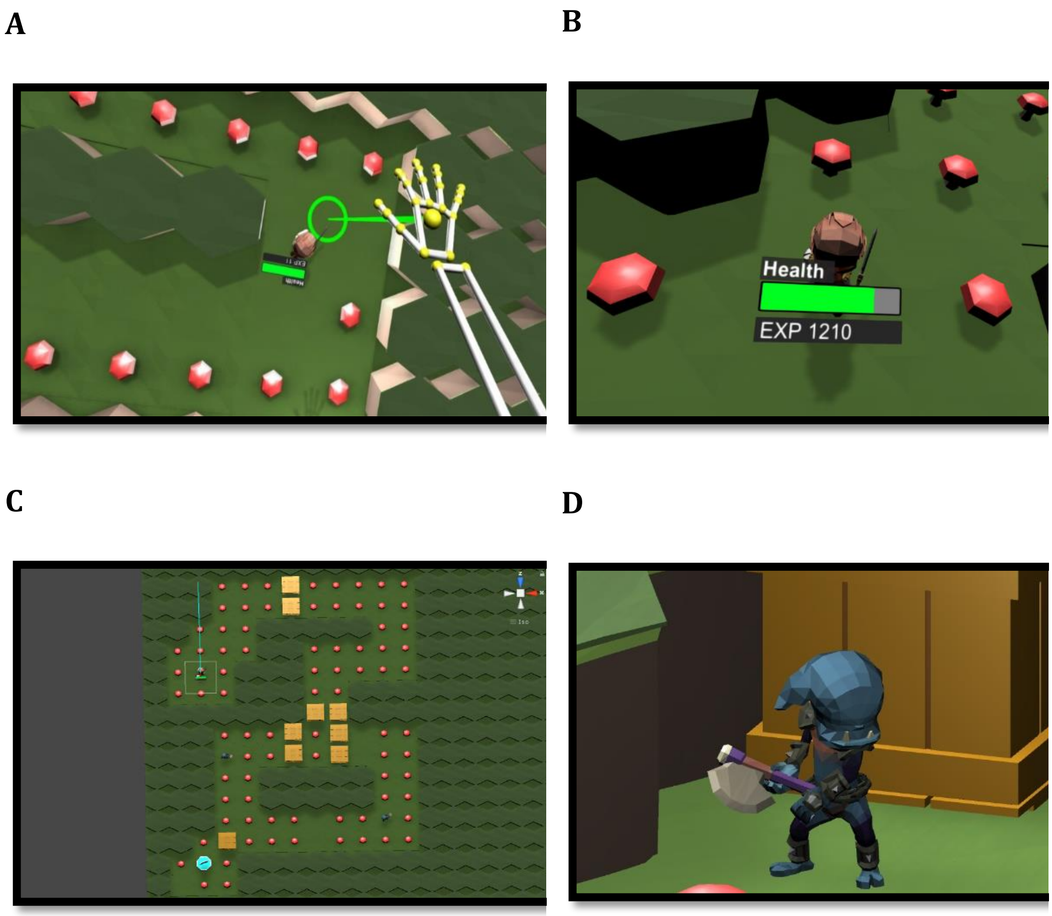



**Figure 7-9: Knight Runs interaction, characters and level design. (A: the 3D cursor and player view for navigating the Knight, B: the knight character and his attributes, C: An example level and the obstacles the player has to navigate, D: the goblin enemies that attacks the player)**

# 8 EVALUATION OF RESTEM WITH ABLE-BODIED PARTICIPANTS

## 8.1 CHAPTER OVERVIEW

This chapter outlines the final study using RESTEM for a longitudinal experiment with able-bodied participants to evaluate RESTEM's competence to measure user movement capability over-time and examine the usability of the system and general system reliability before conducting a study with upper limb impaired participants.

## 8.2 AIM AND OBJECTIVES

The overall aim of this experiment was to evaluate RESTEM and its games with able-bodied users so that the design could be tested and improved for future experiments with upper limb impaired users. Testing with able-bodied participants also gives the opportunity for the refinement of the adaptive algorithms before evaluation with upper limb impaired users.

This experiment had two main objectives:

1. Investigate the usability, acceptability, and technical performance of the first prototype of RESTEM to provide reaching and touching rehabilitation exercises.
2. Investigate the playability and the design of the different games included in RESTEM.
3. Investigate the capability for RESTEM to adapt to user movement capability over a long-term period

Experimental data was obtained quantitatively via user data within TAGER, and qualitative data were obtained from questionnaires and semi-structured interviews.

# 8.3 METHOD

## 8.3.1 EXPERIMENT DESIGN

This experiment had a longitudinal research design, the participants recruited were asked to use RESTEM for a total of ten sessions over five weeks (two sessions a week). The study was approved by Ulster University's research ethics committee and carried out in a private room on the Coleraine campus of Ulster University. The room and equipment setup was identical for each participant.

## 8.3.2 PARTICIPANTS

The recruitment of able-bodied participants facilitated the evaluation of the VR system's capabilities to measure user movement capability, and the testing of the usability of the system and general system reliability before conducting a study with upper limb impaired participants. Eligibility for this study is summarised in Table 8-1. Only Adults (18+) were eligible, who had a completely independent range of movement of their fingers, hands, arms, shoulders, neck, and head. Participants were excluded who suffered from vision problems such as blurred vision, double vision, light sensitivity, colour distortion or depth perceptions issues that were unable to be corrected by spectacles. Information concerning a participant's eligibility was obtained through a pre-assessment demographic and inclusion questionnaire (APPENDIX K) given prior to their agreed involvement in the study. Participants were recruited from students and staff at Ulster University. Initially, emails were circulated throughout the university to recruit participants along with scheduling information sessions to recruit more volunteers. Volunteers that agreed to participate in the study from the email or information sessions were given an information sheet (APPENDIX M), consent form (APPENDIX L) and demographic and inclusion questionnaire prior to their participation in the study. Once consent was given, and the volunteer was eligible for the inclusion questionnaire, a date and time was agreed to begin the study.

**Table 8-1: The eligibility criteria for the study**

| Inclusion Criteria | Exclusion Criteria |
|---|---|
| Males or Females ≥ 18 years old<br><br>A complete independent range of movement of their fingers, hands, arms, shoulders, neck, and head. | Suffering from vision problems such as blurred vision, double vision, light sensitivity, colour distortion, depth perception issues<br><br>Unwilling or unable to consent. |

## 8.3.3 HARDWARE AND SOFTWARE

RESTEM was designed and developed using the Unity game engine. RESTEM ran on an Alienware X51, VR compatible, 64-bit Windows 10 PC with Intel Core i5 @ 3.5GHz, 8GB RAM, and 1TB hard drive (DELL, USA). A Leap Motion controller was used as the main interaction with the VE and was attached centrally on to the VR headset, with the Leap Motion Controller's tracking space and infrared cameras pointing in the forward direction of the participant. The VR headset used, was the recent commercially available Oculus CV1 VR headset and was constantly worn by the participant instead of wearing it intermittingly like the previous two studies. A PC monitor was also used, but this was mainly for the investigators to review the actions of the participant and ensure health and safety throughout the experiment.

## 8.3.4 EXPERIMENT SETUP

In the initial session, the participant gives consent, and the user is evaluated for inclusion in the study through the demographic and inclusion questionnaire. The participant is instructed on how to use the hardware and software through a demonstration by the investigator. The demonstration is only given once at the beginning of the participant's first session; this is to investigate the learnability of the system as an indication of usability. The participant goes through two stages in each session (n=10), the two stages consist of the following:

1. *Official RESTEM* – When the participant is ready to begin they are asked to place the VR headset on, the participant beginning with the calibration of each session calibrating the participant's movement space and upper limb strengths. After calibration, the user enters a relaxing virtual living room. This is the user hub and from here the user to view performance,

achievements and access the VR rehabilitation games. The participant is asked to play three VR games as follows:

a. Fetch – is a VR experience that places the participant in a virtual garden with a virtual dog. The user picks a tennis ball from the air and throws the ball anywhere, and the dog runs to fetch the ball and return it to the participant. The user is asked to pick 27 tennis balls in different locations; the user does these seven times (27*7 =189) for adequate data collection for adaptation.
b. Cannon Grab – this game shows the participant a medieval environment and five barrels in front of the user. The participant grabs cannon balls from the air, trying to place them in one of the highlighted barrels to get the highest score. Again, similar to Fetch the user picks cannon balls in different locations for a total of 189 objects (27*7).
c. Knights Run – is an adventure and maze running game, the user uses their hand to navigate a medieval knight through a maze collecting items, smashing obstacles and fending off enemies to get to the get a high score. This game was designed with more complex game mechanics than the others to evaluate the user experience and acceptance before using with upper limb impaired users, as it could be physically and mentally challenging for those users.

2. *Discussion* – At the end of each session the user is given a questionnaire to gather information on their experience, usability and their perception of performance. A semi-structured interview with the investigator was also conducted. The interview aimed to gather a deeper understanding of the user's feedback and encourage each participant to comment further on their experience with RESTEM.

# 8.4 RESULTS

This experiment recruited seven participants, five males and two females with a mean age of 42 years old, for a five-week period. One of the participants recruited was not included in the data analysis due to experience motion sickness while playing Knight's Run. Table 8-2 describes each participant's demographic information showing their computer and game usage and mean time taken to complete all the sessions.

**Table 8-2: Participant demographics, game, and hardware information**

| User | Age | Gender | Type of games | Time playing games | NUI? | Dominate Arm | PC hrs. | Pointing device? |
|---|---|---|---|---|---|---|---|---|
| 3001 | 51 | M | Board, Casual, Handheld, Console/PC | Once a week | YES | R | 15-40 | Mouse |
| 3002 | 24 | F | Handheld, Console/PC | Once a day | NO | R | >40 | Mouse |
| 3003 | 44 | M | Crossword, Board, Casual, Handheld, Console/PC | Once a day | NO | R | 15-40 | Trackpad |
| 3004 | 57 | M | Crossword | Once a day | YES | R | 15-40 | Mouse, Trackpad |
| 3005 | 39 | F | Board | Rarely | NO | L | 15-40 | Mouse, Trackpad |
| 3006 | 32 | M | Casual | Once a month | NO | R | >40 | Mouse |
| 3007 | 44 | F | Crossword, Casual, Console/PC | Once a week | YES | R | >40 | Mouse |

## 8.4.1 ADAPTIVE DIFFICULTY ADJUSTMENT ANALYSIS

To evaluate RESTEM's capability to adapt task difficulty to the participant's movement capabilities. Results from the previous studies showed that participants had a high diversity of mobility and emphasised the importance of focusing on individuals. In this section, the participant results over ten sessions (S) are presented. Regression analysis to evaluate the participant's user movement profile was used. Initial analysis of the linear regression coefficients of Fitts Law particularly the regression line gradient coefficient indicates the level of difficulty of the tasks. A regression line gradient value that decreases over the ten sessions can potentially indicate an improvement in the participant's movement performance as they are becoming faster, indicating that the user was finding the tasks easier. Evaluating the remainder of the user's movement profile and the qualitative results received from the post questionnaires and the semi-structured interviews may provide additional and supporting information.

### 8.4.1.1 SUMMARY RESULTS

In Table 8-3, is the analysis of the average user profiles across all users, the regression line gradient coefficient shows that the participants showed higher values in the first three sessions (Figure 8-1) which suggests that users were finding it difficult at the start of the experiment this indicates a learning effect as none of the participants had experienced the RESTEM before. The rest of the sessions began to have a generally steady regression line gradient suggesting the users found the task easier. Descriptive statistics of the residuals of the regression shows signs that users had better control of their movements over the ten-sessions. Standard deviation showed a gradual decline showing most user movement times were closer to the regression line indicating improved accuracy more often. Kurtosis and skew also began to decline over the ten-sessions but remained positive (Figure 8-2). The declining positive kurtosis value shows that the users were experiencing less high movement times less often and skew values declining showed that user had movement times that were towards a more symmetric distribution above and below the regression line indicating the user's movement speed seem to steady or become optimal. Mean MT showed similar results to skew to support these results.

**Table 8-3: Average user profile across all participants**

| Profile | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Descriptive statistics | | | | | | | | | | |
| Standard Deviation | 0.458 | 0.858 | 0.463 | 0.457 | 0.364 | 0.343 | 0.410 | 0.335 | 0.389 | 0.336 |
| Kurtosis | 1.830 | 2.146 | 1.611 | 2.070 | 1.975 | 1.537 | 1.223 | 1.267 | 1.393 | 1.092 |
| Skewness | 1.016 | 1.110 | 0.970 | 1.084 | 0.966 | 0.958 | 0.868 | 0.835 | 0.821 | 0.814 |
| Regression statistics | | | | | | | | | | |
| R-Squared | 0.118 | 0.102 | 0.093 | 0.101 | 0.099 | 0.081 | 0.104 | 0.149 | 0.118 | 0.095 |
| Gradient (b) | 0.139 | 0.311 | 0.166 | 0.060 | 0.053 | 0.042 | 0.044 | 0.096 | 0.092 | 0.074 |
| Y-Intercept (a) | 0.671 | - 0.036 | 0.366 | 0.767 | 0.756 | 0.748 | 0.817 | 0.477 | 0.527 | 0.587 |
| Performance statistics | | | | | | | | | | |
| Mean MT | 1.086 | 1.207 | 1.072 | 0.950 | 0.906 | 0.888 | 0.966 | 0.871 | 0.907 | 0.893 |
| Hits | 34 | 20 | 21 | 22 | 22 | 22 | 22 | 22 | 22 | 22 |
| Misses | 0 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Overshoots | 9 | 6 | 6 | 7 | 8 | 6 | 7 | 7 | 8 | 8 |

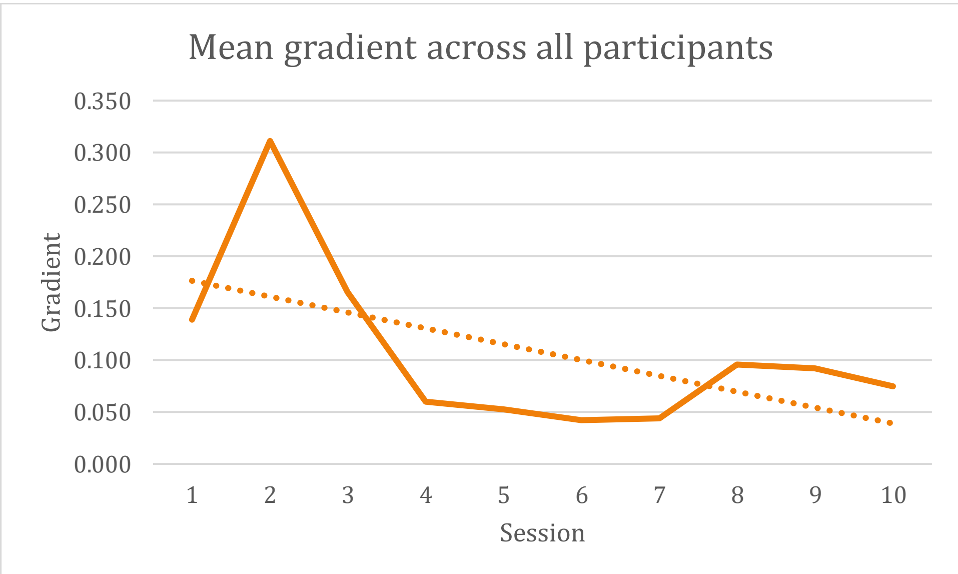



**Figure 8-1: The average line graph for all participants of the gradient coefficient for all ten sessions**

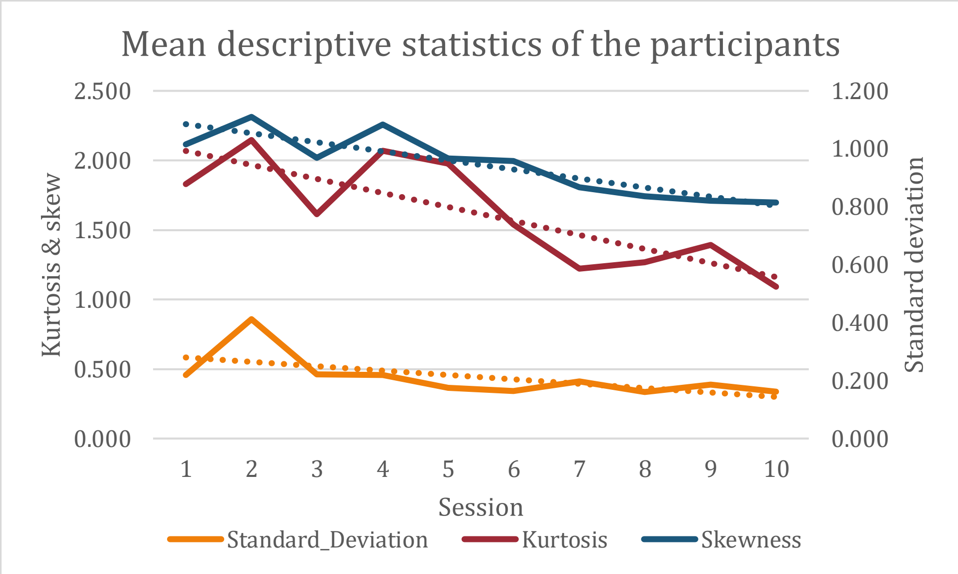



**Figure 8-2: The average descriptive statistics across all participants for all ten sessions**

## 8.4.1.2 ANALYSIS OF INDIVIDUAL PARTICIPANTS

### *8.4.1.2.1 PARTICIPANT 3001*

Over sessions, participant 3001's user movement profile showed an improved performance. 3001 became 11.5% quicker, reduced the number of overshoots by more than half while recording zero timeouts in every session, having an average of one hand lost in the first session, but zero hand loses all other sessions. The standard deviation of MTs from the line generated by Fitts Law regression analysis decreased by 59.2% indicating an improvement in accuracy. Kurtosis from the same analysis decreased by 98.2% bringing the distribution closer to a normal distribution, illustrating a lot less MT outliers (potential overshoots, hand loses). Skew decreased but remained positive showing data points were more symmetric along the regression line, that there were nearly as many slower movement times as fast movement times. An 84.3% decrease in the regression line gradient coefficient suggests the user was finding the task less challenging by the last session. $R^2$ (57.5%) reduced also show the user predictability was possibly lowering. User feedback (Table 8-4) suggests the user thought their movement had improved, along with their understanding of the instructions and tasks involved. 3001 expressed that remembering how to use RESTEM from the previous sessions was very easy. Enjoyment was very high since the first session and indicated that they never got bored during any of the sessions.

**Table 8-4: 3001's feedback on overall performance and usability of RESTEM**

| Key | (1-10) | | | | (0-5) | | |
|---|---|---|---|---|---|---|---|
| | Bad - Good | | | | e.g. Tired – Extremely Tired | | |
| S | Performance (1-10) | Understand (1-10) | Memory (1-10) | Enjoy (1-10) | Tired (0-5) | Frustrating (0-5) | Boring (0-5) |
| 1 | 7 | 8 | 1st session | 9 | 2 | 1 | 0 |
| 2 | | | 9 | 9 | 2 | 0 | 0 |
| 3 | | | | 9 | 0 | 0 | 0 |
| 4 | | | | 9 | 1 | 1 | 0 |
| 5 | | | | 9 | 1 | 1 | 0 |
| 6 | | | | 9 | 0 | 1 | 0 |
| 7 | | | | 9 | 1 | 1 | 0 |
| 8 | | | | 9 | 1 | 1 | 0 |
| 9 | | | | 10 | 0 | 0 | 0 |
| 10 | 10 | 10 | 10 | 10 | 0 | 1 | 0 |

Figure 8-3 shows 3001's line graph, plotting the regression line gradient coefficients from their user movement profile for all their sessions. A trendline is drawn to indicate the direction of the regression line gradient coefficients. Participant 3001 had a negative trendline indicating that the regression line gradient values were reducing thus the participant was finding the tasks easier over the ten sessions. However, sessions one and two had high regression line gradient coefficients in their movement profiles, potentially indicating a greater difficulty for the user (Figure 8-5). This may be indicative of the participant still learning how to perform the reaching tasks as this would be expected when they first use RESTEM. The participant mentioned they were more tired in the first two sessions than any other session (Table 8-5). Learning the system's novel hardware and interactions may have contributed to the fatigue of the participant. After the first two sessions, it seems this user's performance became more stable with more consistent movements. The participant gradually became quicker with their movements (mean MT), the standard deviation of the regression residuals decreased and began to steady over the sessions indicating that 3001 had consistent accuracy in his movement, overshoots did reduce since the beginning supporting the improved consistency in movement. In Figure 8-4 the standard deviation after session two onwards shows a steadier line. Kurtosis and skew showed declining values over the sessions. This consistency in performance after the first two learning sessions produced stable levels of predictability ($R^2$) seen in Figure 8-3.

**Table 8-5: Participant 3001's average user profile per session for all ten sessions of RESTEM**

| S | Standard Dev | Kurtosis | Skew | $R^2$ | Gradient | Intercept | Hand lost | Time outs | Over shot | Mean MT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.453 | 3.666 | 1.430 | 0.123 | 0.076 | 0.640 | 1 | 0 | 13 | 0.861 |
| 2 | 0.529 | 1.396 | 0.885 | 0.126 | 0.156 | 0.459 | 0 | 0 | 6 | 0.886 |
| 3 | 0.215 | 1.993 | 1.051 | 0.055 | 0.019 | 0.706 | 0 | 0 | 6 | 0.764 |
| 4 | 0.220 | 0.992 | 0.851 | 0.081 | 0.018 | 0.682 | 0 | 0 | 8 | 0.746 |
| 5 | 0.210 | 1.074 | 0.895 | 0.042 | 0.015 | 0.765 | 0 | 0 | 3 | 0.808 |
| 6 | 0.212 | 1.573 | 0.861 | 0.070 | 0.032 | 0.624 | 0 | 0 | 5 | 0.722 |
| 7 | 0.199 | 0.414 | 0.555 | 0.075 | 0.012 | 0.772 | 0 | 0 | 8 | 0.816 |
| 8 | 0.249 | 0.753 | 0.681 | 0.038 | 0.035 | 0.680 | 0 | 0 | 5 | 0.792 |
| 9 | 0.189 | 0.072 | 0.274 | 0.072 | 0.028 | 0.699 | 0 | 0 | 5 | 0.787 |
| 10 | 0.184 | 0.066 | 0.730 | 0.052 | 0.012 | 0.723 | 0 | 0 | 6 | 0.762 |

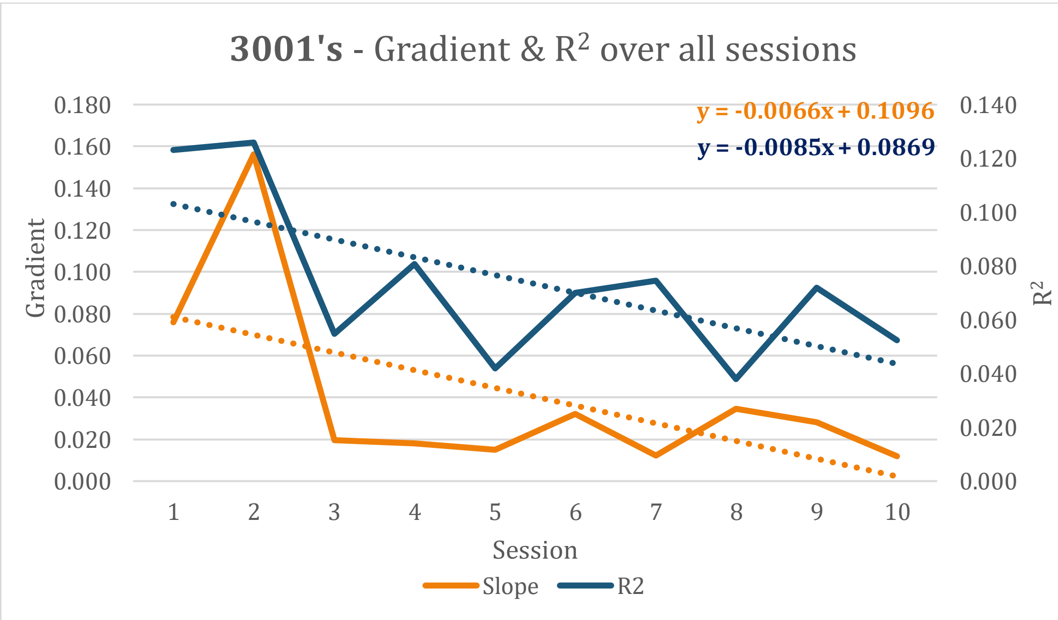



**Figure 8-3: Participant 3001's line graph of gradient $R^2$ statistics for all ten sessions**

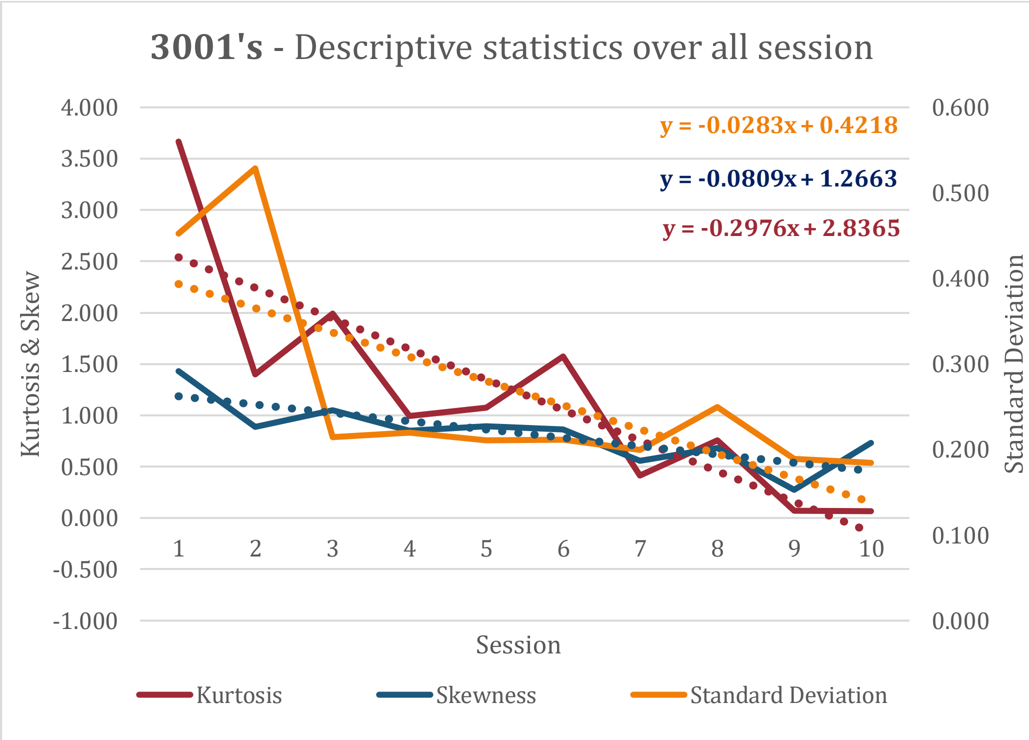



**Figure 8-4: Participant 3001's Descriptive statistics for all ten sessions**

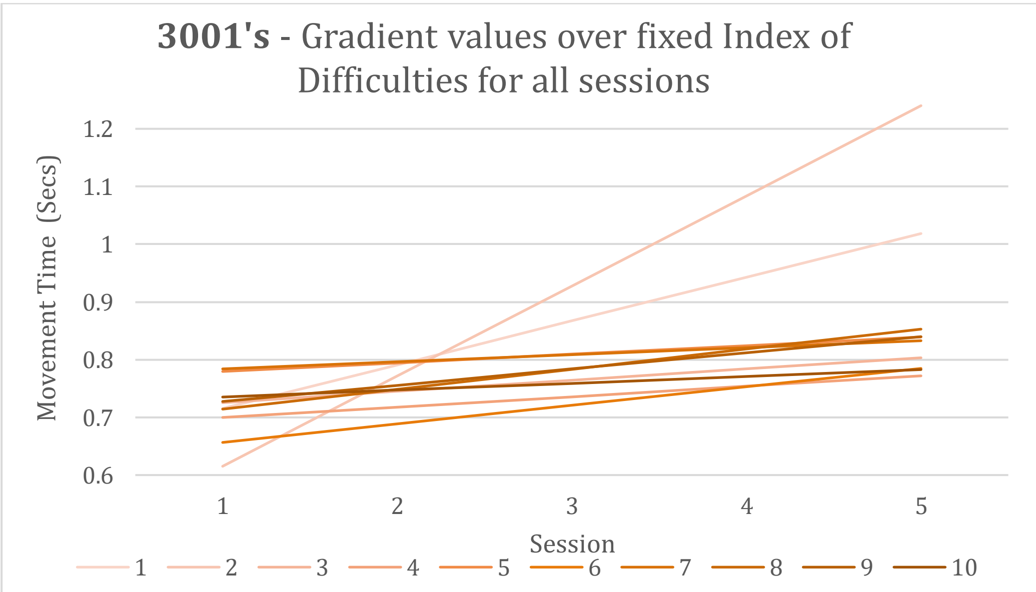



**Figure 8-5: Participant 3001's line gradients for all ten sessions**

#### *8.4.1.2.2 PARTICIPANT 3002*

In Table 8-7, participant 3002 seems to improve their movement performance over the ten sessions. After the ten sessions the participant became 47.2% quicker in their movements, overshoots decreased by 46.2% and she recorded no mean hand loses or timeouts in any of her sessions of RESTEM. This suggests an improvement in the participant's target acquisition performance. Standard deviation (81.8%), kurtosis (36.2%) and skew (25.9%) of the residuals of the regression line all decreased suggesting the better organisation of the movement by the participant. Regression statistics such as $R^2$ (7.2%) show a better fit of the regression to the participant movement data; regression line gradient coefficient decreased by 90.8% showing that after adjustments of the target size the user was finding the movement tasks less difficult. Participant feedback in Table 8-6, she mentioned she felt performance had improved over the ten sessions, she understood the tasks well by scoring a high understandability rating at the beginning and a higher score by the end of all sessions. She could very easily remember the task performed from the previous session and had a very high enjoyment score throughout all sessions. The participant got tired more often during most of the sessions and was bored in 8 out of the ten sections. However, she was bored with the Fetch VR experience only.

**Table 8-6: 3002's feedback on overall performance and usability of RESTEM**

| | **(1-10)** | | | | **(0-5)** | | |
|---|---|---|---|---|---|---|---|
| | Bad - Good | | | | e.g. Tired – Extremely Tired | | |
| S | Performance (1-10) | Understand (1-10) | Memory (1-10) | Enjoy (1-10) | Tired (0-5) | Frustrating (0-5) | Boring (0-5) |
| 1 | 5 | 8 | 1st session | 9 | 4 | 0 | 0 |
| 2 | | | 10 | 10 | 3 | 0 | 0 |
| 3 | | | | 10 | 0 | 0 | 3-Fetch |
| 4 | | | | 10 | 4 | 0 | 3-Fetch |
| 5 | | | | 10 | 4 | 0 | 3-Fetch |
| 6 | | | | 10 | 4 | 0 | 3-Fetch |
| 7 | | | | 10 | 4 | 3-Fetch | 3-Fetch |
| 8 | | | | 10 | 0 | 0 | 3-Fetch |
| 9 | | | | 10 | 3 | 0 | 3-Fetch |
| 10 | 8 | 10 | 10 | 10 | 0 | 0 | 3-Fetch |

The regression line gradient coefficient showed a negative trendline (Figure 8-6) indicating a decrease in the level of difficulty found by the participant over the ten sessions. This user's first session recorded a steep regression line gradient suggesting the user found the reaching tasks difficult. In the same session, the user had a slow Mean MT (1.103secs) and recorded the highest number of overshoots (15) resulting in less coordinated movement, this may have occurred as the user was still learning to use the system. After the first session values began to steady over the rest of the sessions except for session five that produced a negative regression line gradient value. In session five the user performance produced a high Kurtosis compared to other sessions which indicate higher movement times from the regression line. Overshoots also increased slightly and $R^2$ was the lowest from all sessions, supporting this argument. Reviewing the discussions with the user in session five, she said her arm got tired but also notably "*I tried to do it as fast I can, it's maybe not a good thing for accuracy*". Her comment seems to correspond with her movement profile that shows an indication of lower accuracy according to the kurtosis, it is possible these higher movement times are produced at smaller IDs suggesting that closer objects were more difficult. With the fast movements of the participant and their level of tiredness, it is possible the user missed closer objects more often and would explain the negative value for the regression line gradient. The mean MT recorded for session five was also one of the quickest movement times for this participant which also explains the participant's comment. The participant's fourth and fifth session resulted in a decline in R2 values. In these sessions, the user's regression line gradient was the lowest and closest to a straight horizontal regression line showing that the users were almost equally as good at reaching targets closer to them as targets further away, they also had a high positive kurtosis. With the low regression line gradient values and high kurtosis, it is possible that higher movement times may have been more dispersed across the regression line, which may have resulted in a lower $R^2$ value. Session six showed similar results but seemed to be improving. The participant said that they felt consistently tired over session three to six, which may have impacted the results.

**Table 8-7: Participant 3002's average user profile per session for all ten sessions of RESTEM**

| S | Standard Dev | Kurtosis | Skew | $R^2$ | Gradient | Intercept | Hand lost | Time outs | Over shot | Mean MT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.522 | 2.089 | 1.244 | 0.133 | 0.190 | 0.508 | 0 | 0 | 15 | 1.103 |
| 2 | 0.294 | 1.334 | 0.966 | 0.102 | 0.055 | 0.682 | 0 | 0 | 6 | 0.842 |
| 3 | 0.245 | 0.420 | 0.755 | 0.112 | 0.046 | 0.698 | 0 | 0 | 8 | 0.841 |
| 4 | 0.272 | 2.082 | 0.970 | 0.056 | 0.017 | 0.725 | 0 | 0 | 9 | 0.778 |
| 5 | 0.167 | 2.548 | 0.843 | 0.048 | -0.011 | 0.692 | 0 | 0 | 10 | 0.656 |
| 6 | 0.193 | 1.016 | 0.949 | 0.065 | 0.029 | 0.594 | 0 | 0 | 7 | 0.680 |
| 7 | 0.193 | 2.559 | 1.077 | 0.152 | 0.064 | 0.459 | 0 | 0 | 7 | 0.654 |
| 8 | 0.165 | 1.023 | 0.508 | 0.189 | 0.063 | 0.452 | 0 | 0 | 9 | 0.669 |
| 9 | 0.238 | 1.383 | 0.655 | 0.118 | 0.057 | 0.512 | 0 | 0 | 11 | 0.705 |
| 10 | 0.219 | 1.448 | 0.959 | 0.143 | 0.071 | 0.448 | 0 | 0 | 9 | 0.681 |

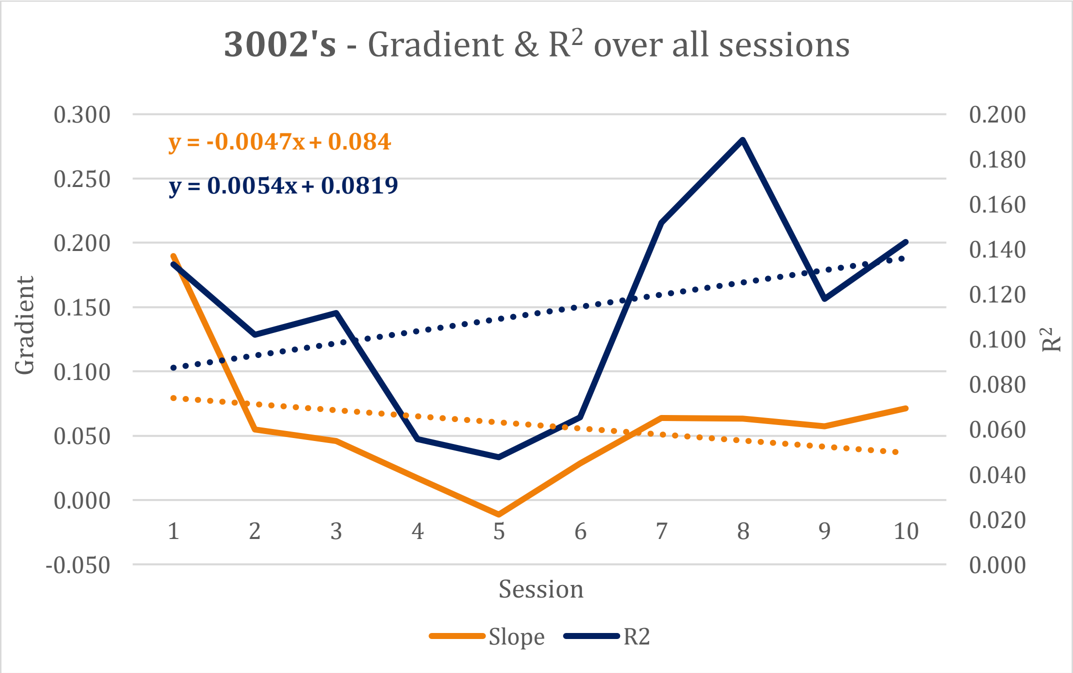



**Figure 8-6: Participant 3002's line graph of gradient $R^2$ statistics for all ten sessions**

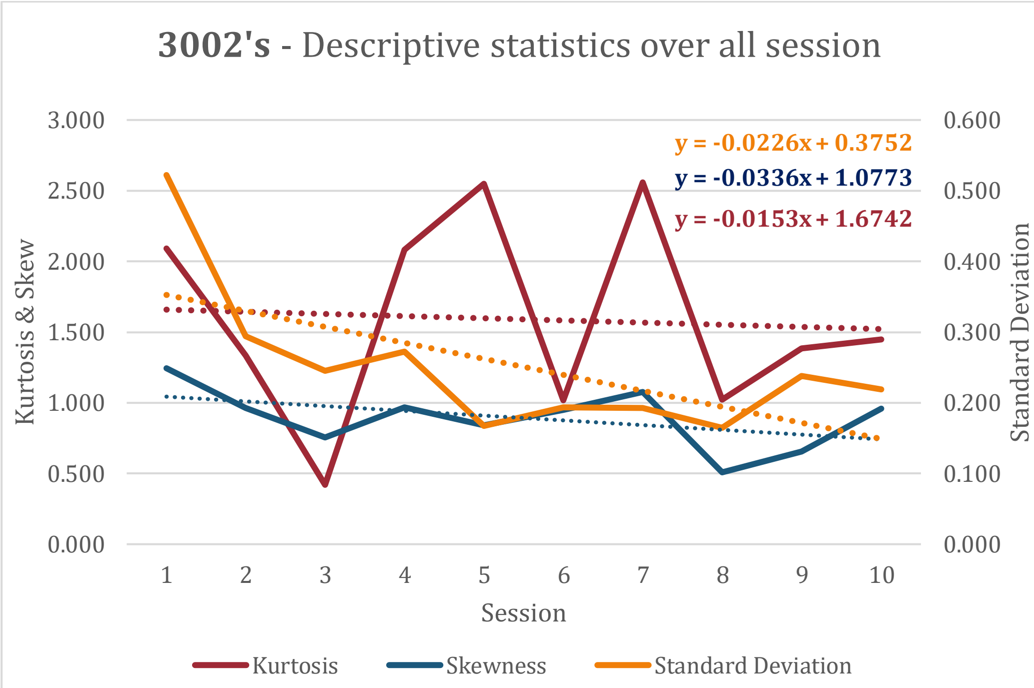



**Figure 8-7: Participant 3002's Descriptive statistics for all ten sessions**

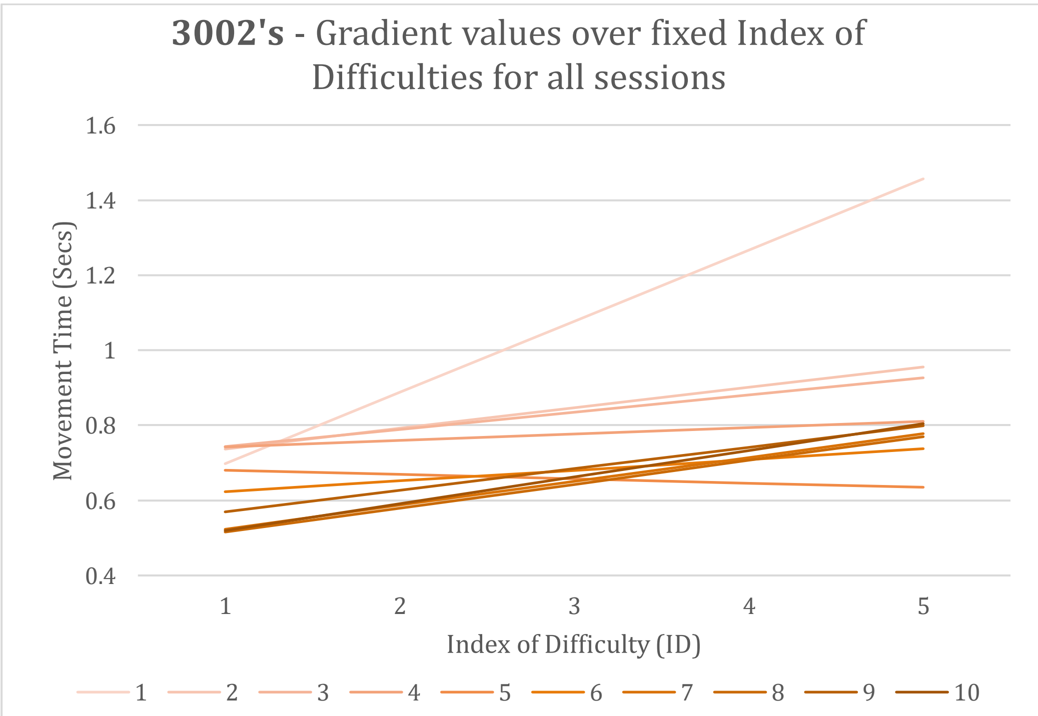



**Figure 8-8: Participant 3002's line gradients for all ten sessions**

#### *8.4.1.2.3 PARTICIPANT 3003*

Participant 3003's user movement profiles showed improved performance over the ten sessions. He was 69.5% quicker and had reduced his overshooting 55.6% by the end of all ten sessions suggests an improvement in target acquisition and movement speed. In only two of the sessions the participant recorded only one timeout, the remaining sessions he had zero timeouts. Standard deviation decreased by 68%, suggesting that the participant is slower to the regression line more often, kurtosis increased 109.3% suggesting larger movement times from the regression line, skew also increased by 6.9%. Although kurtosis increased the participant still improved their fit to the regression line by 4.7%, the decreased value in standard deviation with more movement time closer to the regression line seems to have produced less impact from kurtosis on the R2. The Regression line gradient decrease showed that the participant found the tasks easier over time and y-intercept decreased by 71.1% indicating quicker movement. The participant felt his performance and understanding of the task improved (Table 8-8). Remembering how to use RESTEM was very easy for him to score high at the beginning of the experiment. Enjoyment remained high throughout the experiment. He did become tired during nine of the ten sessions and frustrated and bored in all sessions.

**Table 8-8: 3003's feedback on overall performance and usability of RESTEM**

| | **(1-10)** | | | | **(0-5)** | | |
|---|---|---|---|---|---|---|---|
| | Bad - Good | | | | e.g. Tired – Extremely Tired | | |
| S | Performance (1-10) | Understand (1-10) | Memory (1-10) | Enjoy (1-10) | Tired (0-5) | Frustrating (0-5) | Boring (0-5) |
| 1 | 6 | 8 | 1st session | 10 | 0 | 1 | 1 |
| 2 | | | 10 | 9 | 1 | 1 | 2 |
| 3 | | | | 9 | 2 | 1 | 1 |
| 4 | | | | 10 | 1 | 1 | 1 |
| 5 | | | | 9 | 1 | 1 | 2 |
| 6 | | | | 9 | 2 | 1 | 2 |
| 7 | | | | 10 | 1 | 1 | 1 |
| 8 | | | | 9 | 1 | 1 | 1 |
| 9 | | | | 10 | 1 | 1 | 1 |
| 10 | 10 | 10 | 10 | 10 | 1 | 1 | 1 |

Examining the regression line gradient coefficient in detail shows a negative trendline over the ten sessions (Figure 8-9), indicating the user was finding the tasks easier. In the first five sessions, the regression line gradient coefficients show diverse movement profiles from the participant (Table 8-9). Session two and four showed steep regression lines; their movement profiles show that reduced accuracy of movement and kurtosis with higher or more movement times further from the regression line. The participant seems to have less coordinated movement, and he also said he was tired and bored in these sessions which may have had an impact. It seems that in sessions 6-10 the participant's regression line gradient values began to stabilise, standard deviation values showed improving the accuracy of movement times and Mean MT became quicker in these sessions. From discussions with the participant; in the later sessions he repeated that his focus was improving his accuracy saying, "*I am trying to improve my accuracy and get less overshoots*" towards improving this he explained "*I am just trying to touch the ball gently rather than go through the ball*" this may explain the slight reduction in overshoots and his improved standard deviation which seems to have resulted in a more stabilised regression line gradient in future sessions, for this participant.

**Table 8-9: Participant 3003's average user profile per session for all ten sessions of RESTEM**

| S | Standard Dev | Kurtosis | Skew | $R^2$ | Gradient | Intercept | Hand Lost | Time outs | Over shot | Mean MT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.478 | 0.541 | 0.587 | 0.086 | 0.097 | 1.156 | 0 | 0 | 9 | 1.469 |
| 2 | 1.226 | 3.605 | 1.124 | 0.086 | 0.232 | 0.542 | 1 | 0 | 8 | 1.209 |
| 3 | 0.332 | 1.037 | 0.767 | 0.101 | 0.057 | 0.926 | 0 | 1 | 7 | 1.086 |
| 4 | 0.435 | 3.231 | 1.419 | 0.140 | 0.140 | 0.477 | 0 | 1 | 7 | 0.882 |
| 5 | 0.338 | 2.711 | 1.125 | 0.162 | 0.085 | 0.577 | 0 | 0 | 6 | 0.810 |
| 6 | 0.299 | 1.328 | 0.930 | 0.088 | 0.044 | 0.704 | 0 | 0 | 6 | 0.831 |
| 7 | 0.323 | 0.504 | 0.590 | 0.099 | 0.062 | 0.851 | 0 | 0 | 5 | 1.035 |
| 8 | 0.341 | 2.751 | 1.112 | 0.141 | 0.088 | 0.555 | 0 | 0 | 6 | 0.798 |
| 9 | 0.264 | 2.701 | 1.164 | 0.135 | 0.088 | 0.528 | 0 | 0 | 5 | 0.764 |
| 10 | 0.235 | 1.844 | 0.629 | 0.090 | 0.060 | 0.549 | 0 | 0 | 5 | 0.711 |

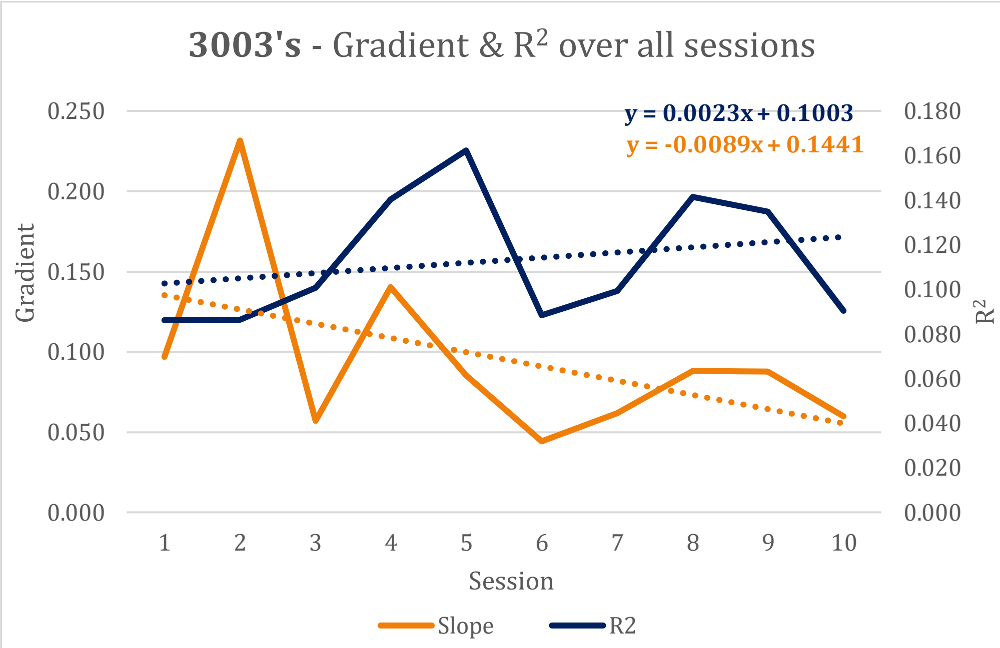



**Figure 8-9: Participant 3003's line graph of gradient $R^2$ statistics for all ten sessions**

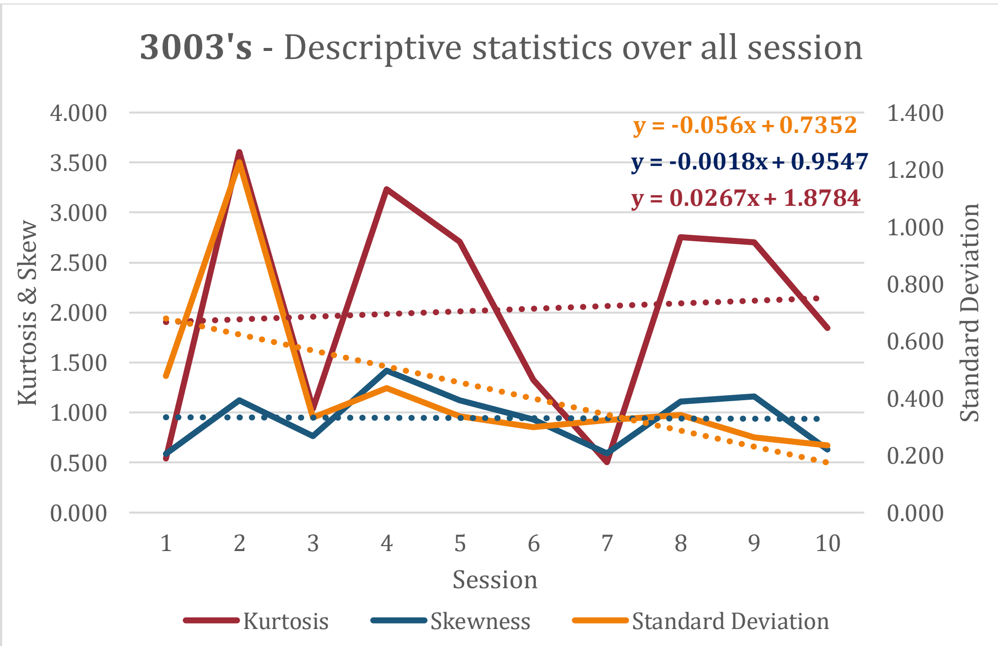



**Figure 8-10: Participant 3003's Descriptive statistics for all ten sessions**

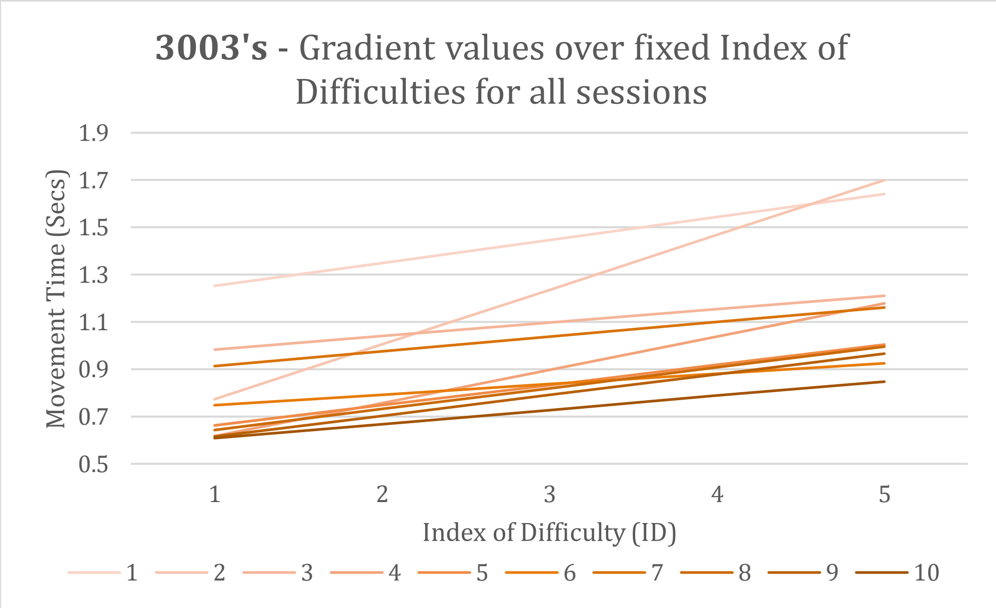



**Figure 8-11: Participant 3003's line gradients for all ten sessions**

#### *8.4.1.2.4 PARTICIPANT 3004*

Participant 3004 is a curious example, it seems that the participant did improve their performance somewhat but was 10.1% slower after the ten sessions and had an increase in the number of overshoots (73.9%). At the first and last session, the user recorded only one timeout, and the remaining sessions had zero timeouts. Improvements in performance were seen in standard deviation with a 19% decrease showing an improvement in accuracy for most of the participant's movements. Kurtosis decreased 61.4 % showing that there were fewer large movement time values recorded. A 4.89% increase in skew suggests the user had more frequent faster movements. Regression statistics show the participant was finding the task easier by the end of the ten sessions, with a 78.8% decrease in the regression line gradient coefficient. Participant feedback in Table 8-10 stated that he found his performance had improved by the end of the ten sessions and felt he understood the tasks and interactions in RESTEM by the end of the experiment. The participant felt he could easily remember how to use RESTEM from the first session (8/10) although it was stated that he could remember most of it by the last session (10/10). He had a consistent high enjoyment score throughout the experiment. This user recorded low tiredness rates most of the time, however, did mention they were more tired during the first and last sessions. This result was similar to frustration levels in the first and last sessions, and the participant did not seem to find any of the sessions boring.

**Table 8-10: 3004’s feedback on overall performance and usability of RESTEM**

| | (1-10) Bad - Good | | | | (0-5) e.g. Tired – Extremely Tired | | |
|---|---|---|---|---|---|---|---|
| S | Performance (1-10) | Understand (1-10) | Memory (1-10) | Enjoy (1-10) | Tired (0-5) | Frustrating (0-5) | Boring (0-5) |
| 1 | 6 | 4 | 1st session | 8 | 3 | 2 | 0 |
| 2 | | | 8 | | 1 | 1 | 0 |
| 3 | | | | | 1 | 0 | 0 |
| 4 | | | | | 1 | 0 | 0 |
| 5 | | | | | 1 | 1- exit button | 0 |
| 6 | | | | | 1 | 0 | 0 |
| 7 | | | | | 0 | 0 | 0 |
| 8 | | | | | 1 | 0 | 0 |
| 9 | | | | | 0 | 0 | 0 |
| 10 | 9 | 9 | 10 | 9 | 3 | 2 | 0 |

Additional analysis of the sessions shows a negative trendline of all the regression line gradient coefficients in each session (Figure 8-12). The first two sessions performed by the participant showed signs of a learning effect, the first session began with the steepest regression line gradient (Table 8-11& Figure 8-14) and had one of slowest mean MT compared to the other sessions. Sessions one and two produced the highest positive kurtosis values indicating the potential for larger or more movement times further from the regression line. After the first session, the regression line gradient values began to decrease from session two – four showing that the participant was finding the tasks easier and the learning factor was dissipating. Sessions five and nine showed a steeper regression line gradient value similar to that of session two where the participant was in a learning phase. These sessions show low standard deviation values showing improved accuracy, kurtosis and skew became a lower positive value. In session five and nine, the participant's standard deviation decreased from the previous session suggesting improved accuracy. Kurtosis and skew also had a lower positive value. It seems that with more movement times becoming closer to the regression line (standard deviation) and skew showing more data points above the regression line than the previous sessions; has resulted in a steeper gradient value along with high positive kurtosis contributing the steeper gradient as there were still high movement times at larger IDs from the regression line.

Session 7 is interesting as the regression line gradient was almost zero (0.006) suggesting the participant was taking the same amount of movement times across IDs values. In session seven the participant had good accuracy and one of the fastest sessions. A lower positive skew shows more symmetric data along the regression. Kurtosis also decreased to a lower positive value suggesting lower movement times compared to any other session. Mean MT value supports this as the participant was fast in this session. However, it is unclear where the movement times that were still considered outliers by the kurtosis lay according to the IDs. It may be that the participant was finding targets located closest just as difficult as those further away, if this is the case it may be useful to know in a future application where the higher movements are recorded in respect to their IDs, this may explain the regression line gradient in more detail. This may also support the analysis of movement zones in the previous Chapter 5.4.1.3. However, movement zone analysis in this experiment was not possible as the quantity of data was not substantial enough to perform regression.

**Table 8-11: Participant 3004's average user profile per session for all ten sessions of RESTEM**

| S | Standard Dev | Kurtosis | Skew | $R^2$ | Gradient | Intercept | Hand Lost | Time outs | Over shot | Mean MT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.350 | 2.125 | 1.060 | 0.095 | 0.096 | 0.635 | 0 | 1 | 6 | 0.912 |
| 2 | 0.250 | 2.612 | 1.401 | 0.092 | 0.065 | 0.607 | 0 | 0 | 8 | 0.822 |
| 3 | 0.204 | 1.174 | 0.894 | 0.078 | 0.027 | 0.765 | 0 | 0 | 6 | 0.864 |
| 4 | 0.294 | 1.951 | 1.217 | 0.040 | 0.022 | 0.821 | 0 | 0 | 10 | 0.904 |
| 5 | 0.253 | 1.556 | 0.919 | 0.083 | 0.064 | 0.668 | 0 | 0 | 12 | 0.900 |
| 6 | 0.301 | 1.761 | 1.041 | 0.050 | 0.058 | 0.661 | 0 | 0 | 9 | 0.876 |
| 7 | 0.215 | 0.975 | 0.866 | 0.065 | 0.006 | 0.818 | 0 | 0 | 10 | 0.839 |
| 8 | 0.193 | 0.397 | 0.753 | 0.097 | 0.019 | 0.795 | 1 | 0 | 10 | 0.858 |
| 9 | 0.197 | 1.655 | 1.000 | 0.179 | 0.066 | 0.643 | 0 | 0 | 14 | 0.894 |
| 10 | 0.288 | 1.127 | 1.114 | 0.064 | 0.042 | 0.856 | 0 | 1 | 13 | 1.009 |

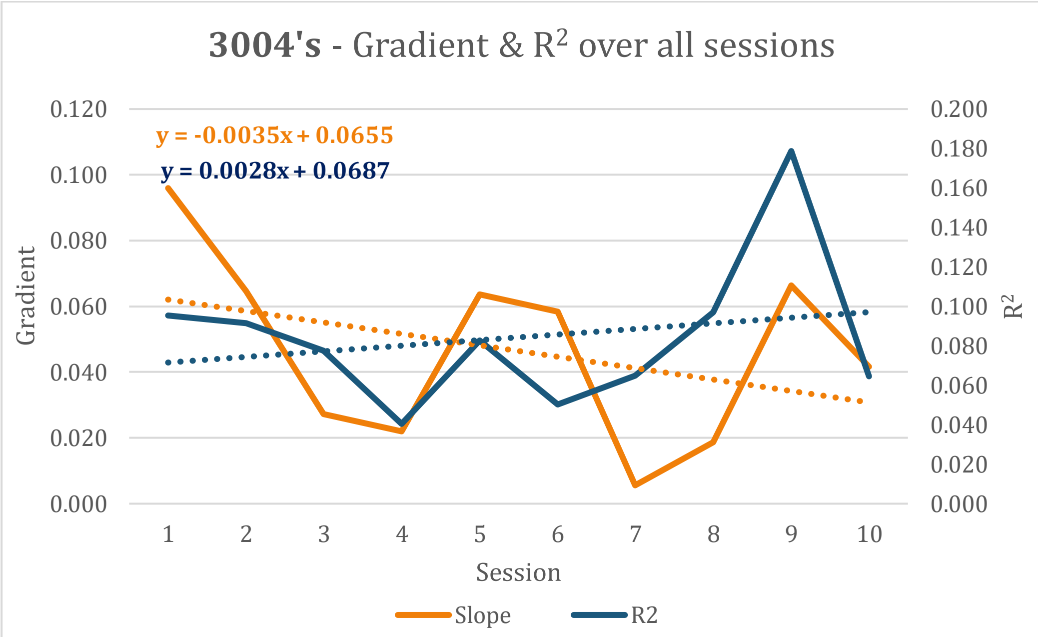



**Figure 8-12: Participant 3004's line graph of gradient $R^2$ statistics for all ten sessions**

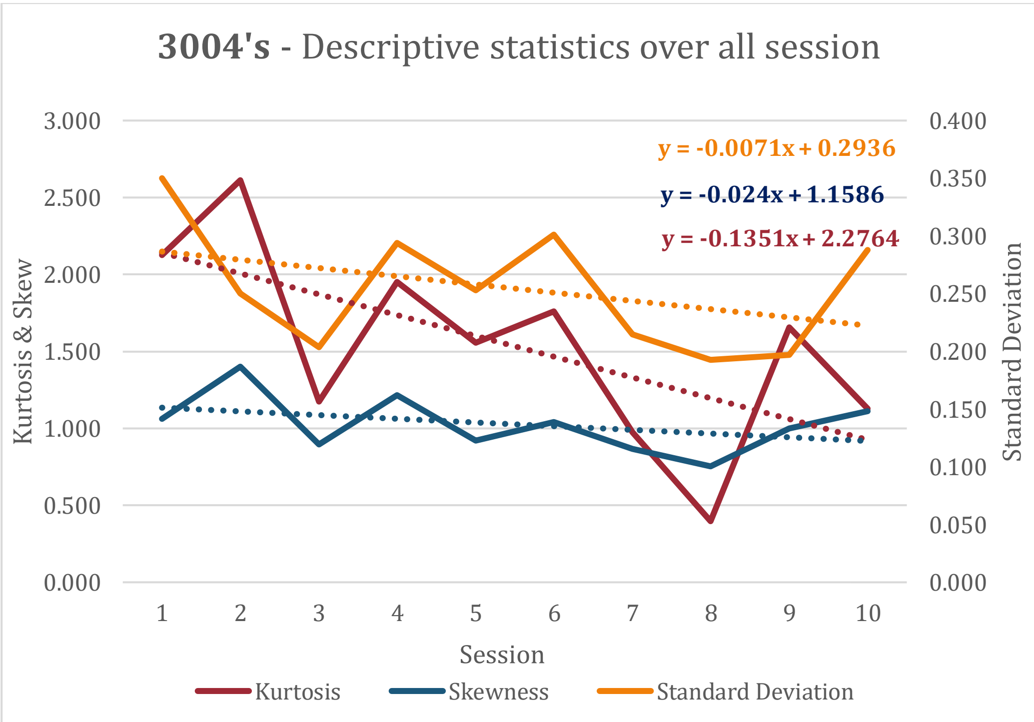



**Figure 8-13: Participant 3004's Descriptive statistics for all ten sessions**

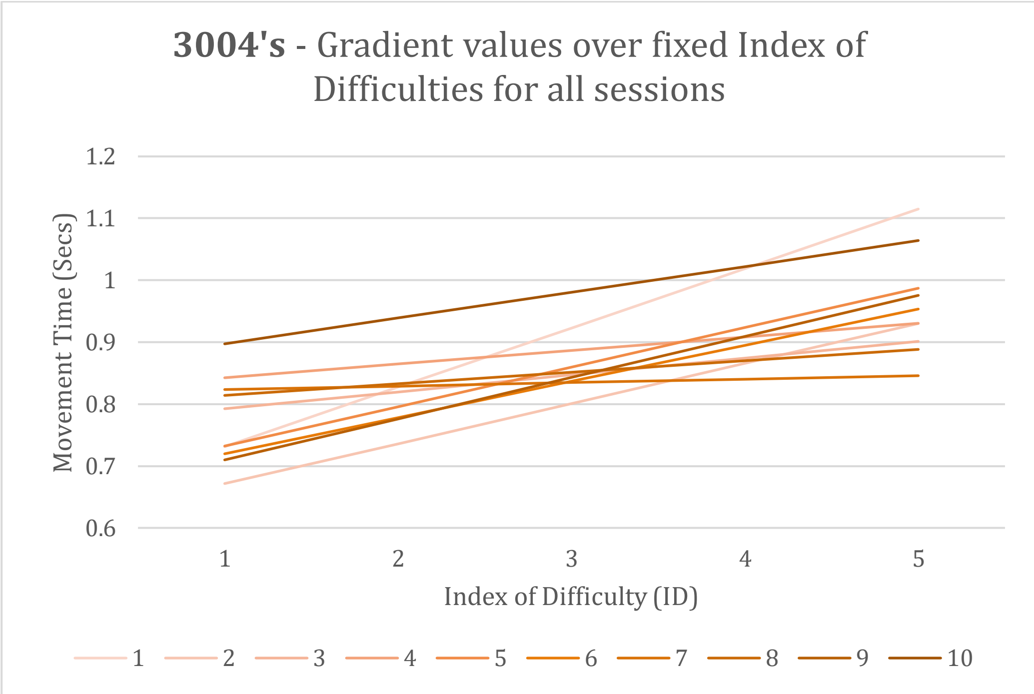



**Figure 8-14: Participant 3004's line gradients for all ten sessions**

#### *8.4.1.2.5 PARTICIPANT 3006*

Mean MT of participant 3006 shows that they slowed down by the time they finished the experiment with an increase of 24.8% in movement time. 12.5% increase in overshoots and 40% increase in timeouts. This suggests that the participant's performance was declining. Standard deviation increased by 46.3% this indicates that he had become more diverse in their movement times the kurtosis decreased by 60% and skew decreased showing slower movement times by the end of all the participant's sessions. The regression line gradient coefficient of the regression showed no change, with the user finding the last session of tasks equally as challenging as the first session. $R^2$ decreased showing less predictability indicating a poorer performance by the participant. Feedback from the participant (Table 8-12) shows that the user felt he had improved his performance and was able to understand what was involved while using RESTEM and he was able to remember the interaction from the first session perfectly throughout the rest of the sessions. 90% of the sessions the participant felt tired during each session.

**Table 8-12: 3006's feedback on overall performance and usability of RESTEM**

| | (1-10) | | | | (0-5) | | |
|---|---|---|---|---|---|---|---|
| | Bad - Good | | | | e.g. Tired – Extremely Tired | | |
| S | Performance (1-10) | Understand (1-10) | Memory (1-10) | Enjoy (1-10) | Tired (0-5) | Frustrating (0-5) | Boring (0-5) |
| 1 | 8 | 9 | 1st session | 10 | 0 | 0 | 0 |
| 2 | | | 10 | 10 | 3 | 0 | 0 |
| 3 | | | | 10 | 2 | 0 | 0 |
| 4 | | | | 10 | 2 | 0 | 0 |
| 5 | | | | 10 | 2 | 0 | 0 |
| 6 | | | | 10 | 2 | 0 | 0 |
| 7 | | | | 10 | 2 | 0 | 0 |
| 8 | | | | 10 | 2 | 0 | 0 |
| 9 | | | | 10 | 1 | 0 | 0 |
| 10 | 10 | 10 | 10 | 10 | 1 | 0 | 0 |

Similar to the participants previously analysed, the trendline of the regression line gradient values were negative. The participant's first three sessions show regression line gradient values that fluctuate considerably. The first session indicated a reasonably good performance from the participant. However, in the second session, the user performance data produced a steep regression line gradient and a movement profile that suggests his motion was not coordinated well enough to efficiently perform the reach and touch tasks. In this session, the user did mention he was tired scoring three out of five on tiredness from the post-questionnaire. Similar results were observed in session three, but the user appeared to be performing better with practice and was less tired in this session (two out of five). After the first three sessions, the participant has user movement profiles that are consistent with regression line gradient values having smaller deviations between sessions. The participants meanMTs were a lot slower than other participants and showed only a gradual decline in movement time suggesting the users was slowly becoming faster. The sessions showed a reduction in standard deviation values, so movement times were closer to the regression line. Kurtosis and skew also showed a decline indicated by the negative trendlines lines in Figure 8-16. It seems that the participants gradually faster movement times, taking more time to acquire the targets has allowed him to become more accurate and produce higher $R^2$ values compared to other participants. During session eight the participant produced a steeper regression line gradient than previous sessions signifying that the tasks where more challenging for the participant. In session eight, kurtosis increased with higher movement times recorded occasionally, skew also increase showing more values below the regression line, and intercept was close to zero. It seems that the high movements suggested by the kurtosis are located at high IDs which has increased the regression line gradient and decreased the regression line intercept. Session eight was fast, as mean MT was one of the lowest. However, the standard deviation was lower than most sessions suggesting improved accuracy. Although the participant was more accurate and faster most of the time, it seems his movement was less coordinated occasionally (higher movement times at larger IDs) resulting in a steeper regression line gradient. Session nine and ten's regression line gradients began to decline indicating a possible improvement in performance by the participant.

**Table 8-13: Participant 3006's average user profile per session for all ten sessions of RESTEM**

| S | Standard Deviation | Kurtosis | Skew | R2 | Gradient | Intercept | Hand lost | Time outs | Over shot | Mean MT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.555 | 1.837 | 1.107 | 0.125 | 0.190 | 0.641 | 0 | 0 | 5 | 1.142 |
| 2 | 2.157 | 2.211 | 1.101 | 0.132 | 1.166 | -3.101 | 0 | 10 | 5 | 2.288 |
| 3 | 1.359 | 2.129 | 1.063 | 0.134 | 0.729 | -1.468 | 0 | 10 | 2 | 1.912 |
| 4 | 1.230 | 2.613 | 0.991 | 0.107 | 0.053 | 1.367 | 0 | 7 | 4 | 1.531 |
| 5 | 0.989 | 2.284 | 0.952 | 0.178 | 0.111 | 1.226 | 1 | 4 | 6 | 1.500 |
| 6 | 0.822 | 1.343 | 0.840 | 0.108 | 0.035 | 1.277 | 0 | 4 | 5 | 1.417 |
| 7 | 0.957 | 1.418 | 1.067 | 0.077 | 0.056 | 1.158 | 0 | 4 | 6 | 1.424 |
| 8 | 0.790 | 1.954 | 1.149 | 0.119 | 0.246 | 0.039 | 0 | 4 | 4 | 1.366 |
| 9 | 1.148 | 0.461 | 0.713 | 0.070 | 0.231 | 0.292 | 0 | 4 | 5 | 1.537 |
| 10 | 0.812 | 0.733 | 0.727 | 0.098 | 0.190 | 0.406 | 0 | 4 | 6 | 1.425 |

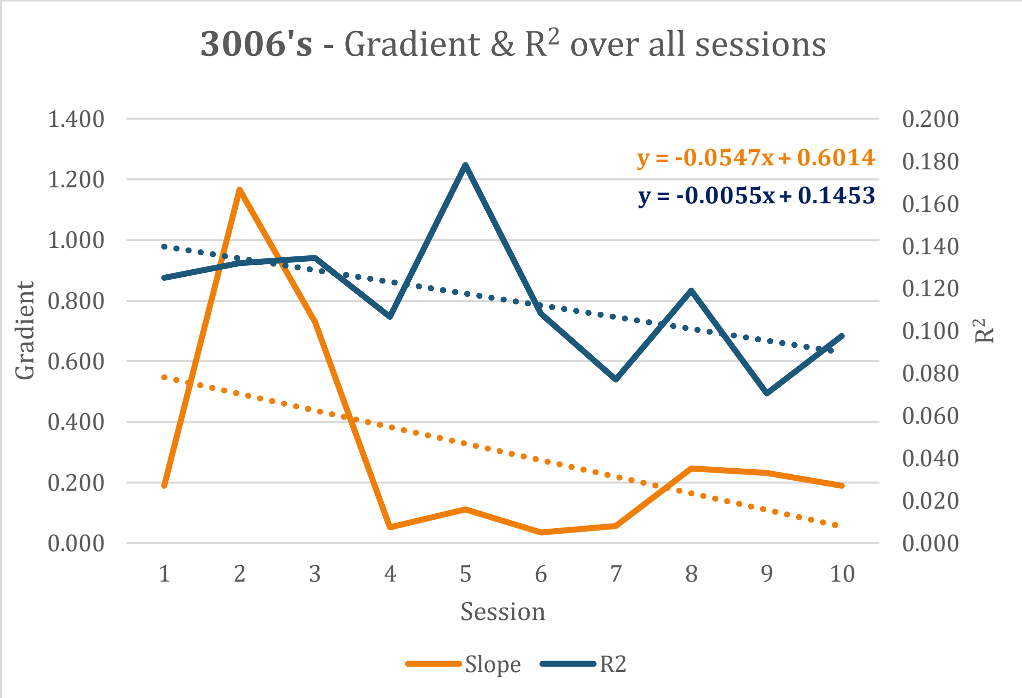



**Figure 8-15: Participant 3006's line graph of gradient $R^2$ statistics for all ten sessions**

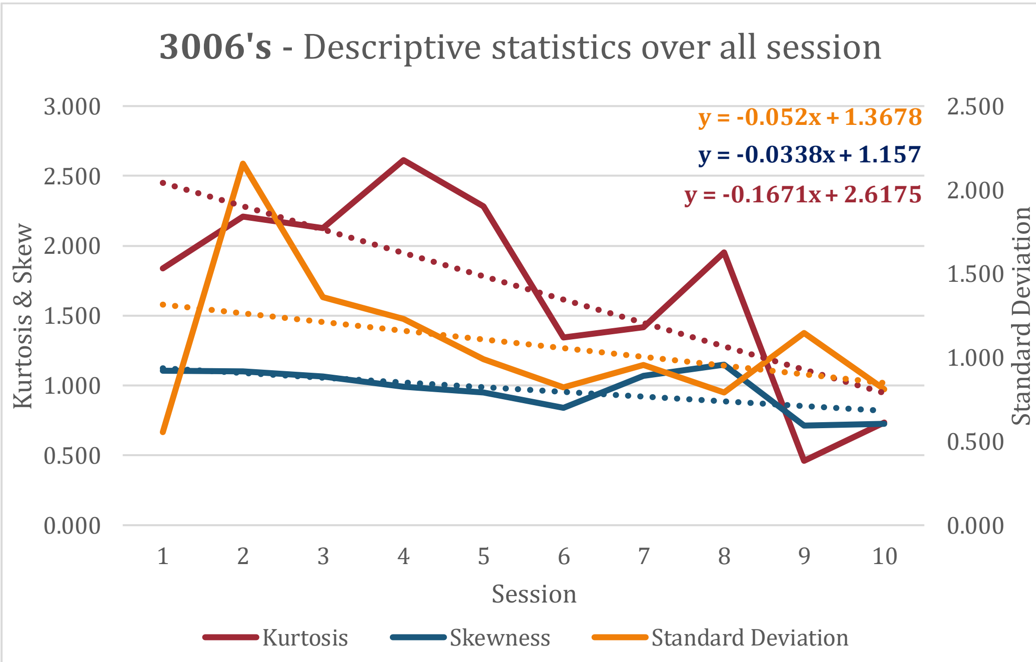



**Figure 8-16: Participant 3006's Descriptive statistics for all ten sessions**

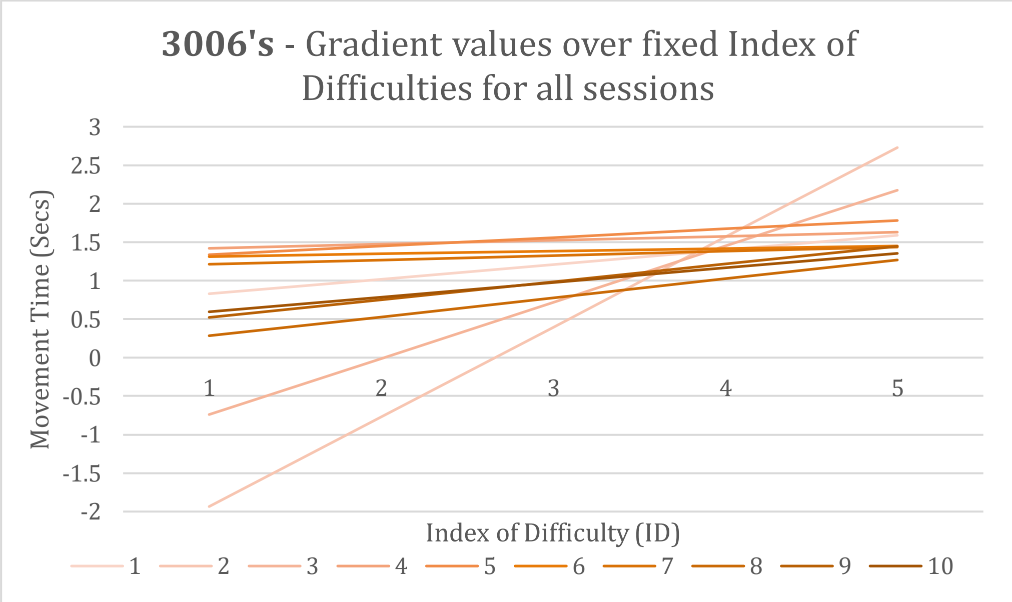



**Figure 8-17: Participant 3001's line gradients for all ten sessions**

### *8.4.1.2.6 PARTICIPANT 3007*

By the end of the experiment, participant 3007 became 25.2% quicker, recording zero timeouts, although overshot (85.3%) the targets more often by the end of the tenth session. A 29.9% decrease in standard deviation indicates a better movement accuracy most of the time. Kurtosis increased by 83.7% with larger movement time occasionally produced by the user. Skew (9.1%) increased signifying quicker movement times more often. The participant found the task easier by the end of the tenth session recording a 61.2% decrease in the regression line gradient coefficient (Table 8-15). However, $R^2$ decreased by 16.7%, explaining less of the participant's movement variation. From the feedback questionnaire, the participant stated that they improved their performance considerably scoring herself three at the first session and a nine by the last session. This was similar for understanding how to use RESTEM score a two at session one and eight at session ten. Their memory of the system remained high throughout the experiment. She felt that she did not enjoy using the system in the first session, but this increased gradually by the end of all sessions. The participant frustration and boredom varied between sessions (Table 8-14).

**Table 8-14: 3007's feedback on overall performance and usability of RESTEM**

| S | (1-10) Bad - Good | | | | (0-5) e.g. Tired – Extremely Tired | | |
|---|---|---|---|---|---|---|---|
| | Performance (1-10) | Understand (1-10) | Memory (1-10) | Enjoy (1-10) | Tired (0-5) | Frustrating (0-5) | Boring (0-5) |
| 1 | 3 | 2 | 1st session | 5 | 3 | 3 | 4 |
| 2 | | | 9 | 6 | 4 | 3 | 4 |
| 3 | | | | 8 | 2 | 1 | 0 |
| 4 | | | | 7 | 4 | 3 | 3 |
| 5 | | | | 7 | 2 | 2 | 3 |
| 6 | | | | 6 | 5 | 5 | 4 |
| 7 | | | | 9 | 4 | 4 | 5 |
| 8 | | | | 7 | 3 | 1 | 3 |
| 9 | | | | 6 | 3 | 4 | 3 |
| 10 | 9 | 8 | 8 | 8 | 4 | 3 | 4 |

Similar to the majority of the participants the participant seemed to be in a learning phase for the first two sessions producing a steep regression line gradient coefficient on both occasions, after the second session the regression line gradient values began to decrease showing signs that the user's movement performance was improving. Figure 8-18 shows the negative trendline of the regression line gradient values for each session. Session 3-5 regression line gradients declined to suggest the participant was continuing to improve and was potentially still learning as she progressed through the sessions. These three sessions show smaller standard deviations and larger positive kurtosis values; the kurtosis indicates a generally accurate performance. However, the participant may have overshot the object on occasions, recording higher movement times from the regression line. The standard deviation shows more values were becoming closer to the regression line supporting a higher accuracy seen from the participant. From session three the participant progressively became quicker over the sessions. Session eight showed an increase in the regression line gradient suggesting the user was finding the task more difficult. However, the intercept produced by the regression possible moving the regression line down showing that this person recorded smaller movement times at lower IDs, the mean MT for session eight was also the fastest. The standard deviation was low, kurtosis, and skew also had a lower positive value showing less high movement times and towards more symmetric data above and below the regression line. Although the participant's regression line gradient was steeper, the remainder of their movement profile suggests they had a good performance, which resulted in the highest $R^2$ values in this session. It seems this person has improved their speed of movement becoming quicker, but their movement accuracy decreased. The user did have a high level of tiredness from the questionnaire, it seems the faster movements may have increased her fatigue and accuracy may have declined as a result.

**Table 8-15: Participant 3007's average user profile per session for all ten sessions of RESTEM**

| S | Standard Deviation | Kurtosis | Skew | R2 | Gradient | Intercept | Hand lost | Time outs | Over shot | Mean MT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.394 | 0.725 | 0.666 | 0.145 | 0.187 | 0.444 | 0 | 0 | 5 | 1.029 |
| 2 | 0.695 | 1.720 | 1.184 | 0.076 | 0.193 | 0.595 | 0 | 0 | 6 | 1.197 |
| 3 | 0.427 | 2.914 | 1.290 | 0.076 | 0.115 | 0.571 | 1 | 0 | 7 | 0.962 |
| 4 | 0.291 | 1.552 | 1.054 | 0.181 | 0.108 | 0.529 | 1 | 0 | 3 | 0.862 |
| 5 | 0.227 | 1.679 | 1.065 | 0.081 | 0.053 | 0.608 | 1 | 0 | 7 | 0.763 |
| 6 | 0.229 | 2.202 | 1.129 | 0.103 | 0.054 | 0.628 | 2 | 0 | 6 | 0.799 |
| 7 | 0.574 | 1.471 | 1.052 | 0.158 | 0.066 | 0.847 | 0 | 0 | 5 | 1.030 |
| 8 | 0.269 | 0.726 | 0.809 | 0.311 | 0.123 | 0.343 | 1 | 0 | 10 | 0.742 |
| 9 | 0.300 | 2.087 | 1.123 | 0.133 | 0.083 | 0.490 | 3 | 0 | 11 | 0.755 |
| 10 | 0.276 | 1.332 | 0.727 | 0.121 | 0.072 | 0.539 | 1 | 0 | 10 | 0.769 |

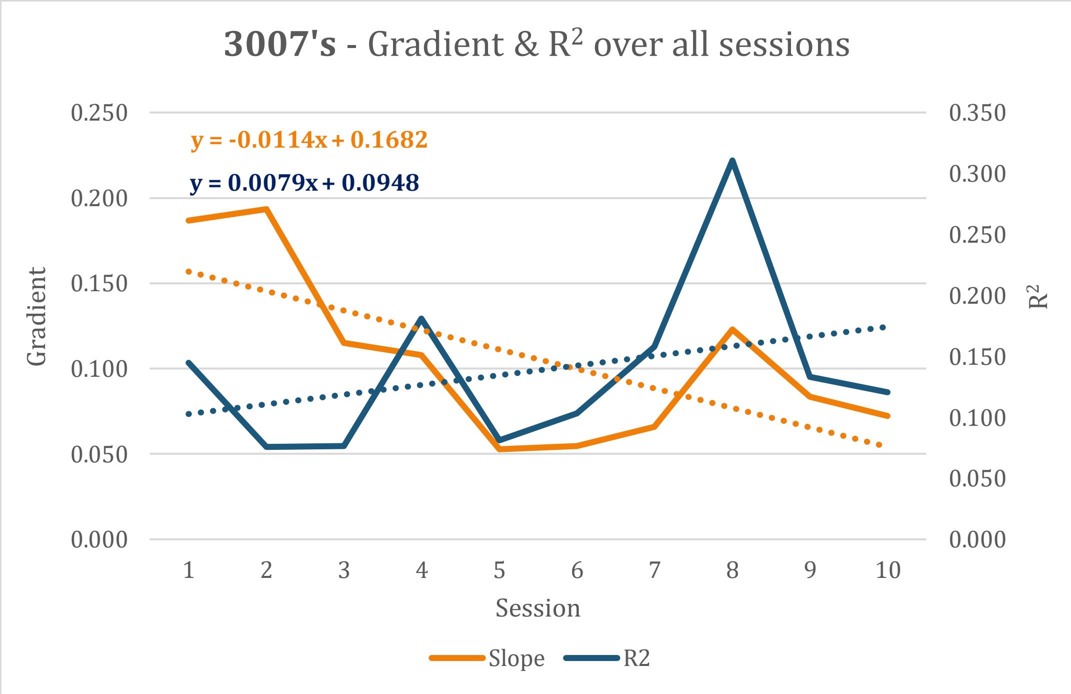



**Figure 8-18: Participant 3007's line graph of gradient $R^2$ statistics for all ten sessions**

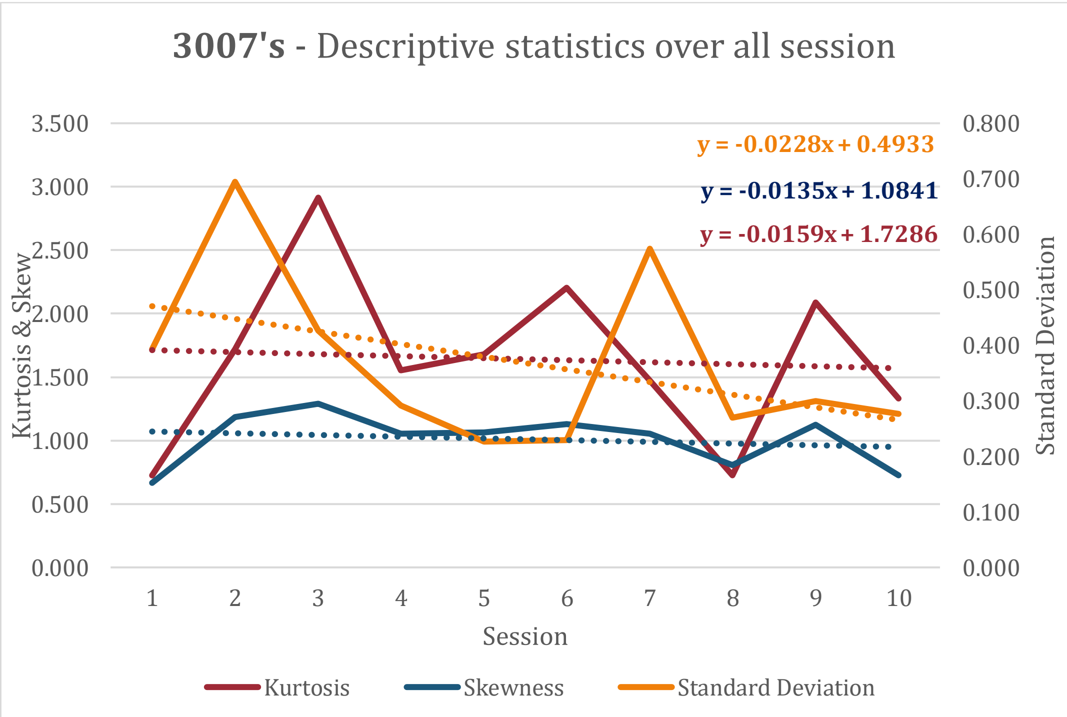



**Figure 8-19: Participant 3007's Descriptive statistics for all ten sessions**

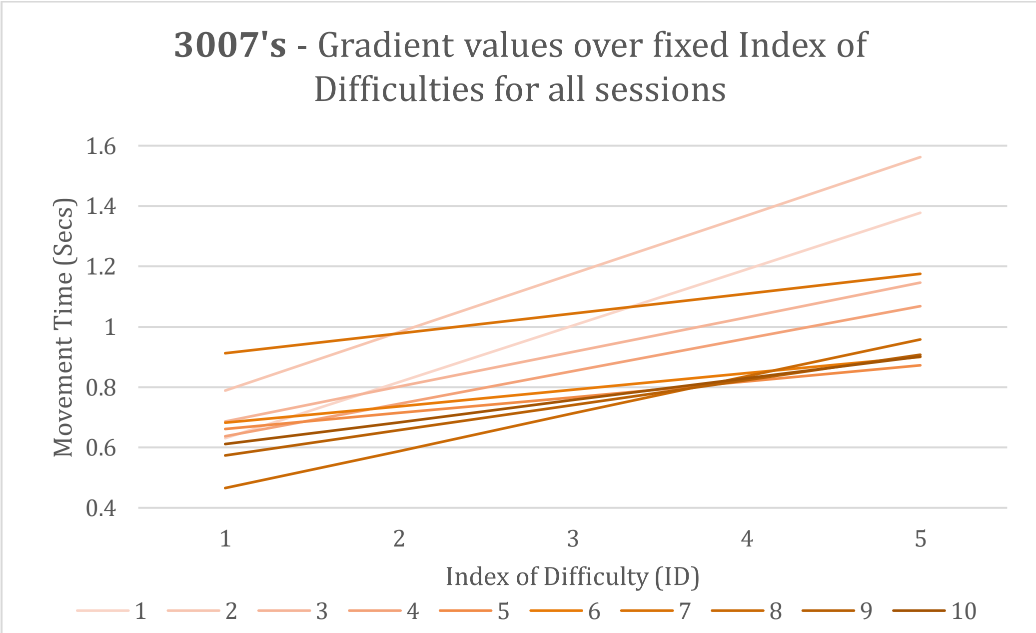



**Figure 8-20: Participant 3007's line gradients for all ten sessions**

## 8.4.2 USABILITY

Feedback on the usability of RESTEM was gathered through the SUS questionnaire and semi-structured interviews after each session. The SUS questionnaire was given to the user after the last session to examine the usability over a longer period. From research, a score above 68 is considered above average usability. The results show that RESTEM had a mean SUS score of 84.2 having a high usability rating. All participants enjoyed using the VR headset and would continue to use it. Most participants experienced a rise in temperature, feeling hot with prolonged use of the VR headset. The Leap Motion Controller was also attached to the VR headset which does get hot with continued use; this may have added to the temperature rise. When the Leap Motion Controllers temperature increases, tracking performance tends to decrease. The usability of any system involves several factors including, easy to understand, learnability, memorability, enjoyability, and ease of use (Lange, Flynn and Rizzo, 2009). The post-questionnaire was given after each session, asking questions related to these factors in Table 8-16. By the end of all ten sessions the participants had rated high values out of ten for all the factors, understanding and memorability had a score of 7.1 or above, enjoyment scored a minimum of 6.9 out of 10 and performance (ease of use) scored a no less than 7.5 out of 10 for the RESTEM application.

**Table 8-16: Participant feedback on usability from the post-questionnaire**

| User | SUS | Preferred VR | Use VR again | Performance | Understand | Memory | Enjoyed |
|---|---|---|---|---|---|---|---|
| 3001 | 100 | YES | YES | 9.4 | 9.8 | 9.8 | 9.2 |
| 3002 | 100 | YES | YES | 9.4 | 9.7 | 9.7 | 9.8 |
| 3003 | 87.5 | YES | YES | 9.1 | 9.7 | 9.7 | 9.5 |
| 3004 | 87.5 | YES | YES | 8 | 7.9 | 7.9 | 8.1 |
| 3006 | 80 | YES | YES | 10 | 9.9 | 9.9 | 10 |
| 3007 | 100 | YES | YES | 7.5 | 7.1 | 7.1 | 6.9 |
| Mean | 84.2 | | | | | | |

For more detail on the usability of RESTEM and its specific components and functionality, the participant was invited by the investigator to discuss and give feedback on the usability of RESTEM after each session. Discussions focused on the feedback of the games and VR experience they interacted with. Below reports on the participants' comments on each of the games, VR experiences and components.

#### 8.4.2.1 CALIBRATION

Most of the users enjoyed the interactions and aesthetics of the calibration. Participants mentioned that the spotlight that expands when the training begins is a good feature for directing attention to the training. One of the main issues among the participants was the ability to understand some of the tasks in their first session of RESTEM. A challenge for most participants was following the instructions for reaction time actions given by Reebo the robot. One participant said, "*it might be good to have a tutorial for each action*" it is possible that observation of a task beforehand may help give clearer guidance on how to perform the tasks correctly. Participant 3002, seemed to ignore or did not understand the instruction and had to be verbally guided through the calibration on the first session, although after the first session the user could remember enough to perform the calibration by themselves. When participants performed the RoM task explained in section 7.3.6.2, it was noticeable that participants where overextending their arm to grab all the balloon objects despite the verbal instructions warning them not to stretch and keep their back straight without leaning forward. This may be a problem when measuring the RoM space as it will cause the user to overextend in the games which is not recommended for rehabilitation.

### 8.4.2.2 VIRTUAL LIVING ROOM

#### *8.4.2.2.1 KNOWLEDGE OF PERFORMANCE FEEDBACK (SAC)*

In the Virtual Living Room, there is a performance display showing knowledge of performance feedback of the participant's performance over-time. The display shows a graph depicting the user's speed, accuracy and consistency (SAC) over multiple sessions. In every session, the participant is placed in the Virtual Living Room allowing them to review their performance. Participants noticed the performance graph, and for two people it seems to have influenced the way they play the games using different strategies to improve their performance statistics. One participant said, "*I tried to slow down to improve my accuracy*". Another participant said that he was focusing on consistency and after reviewing his performance he noticed it was not as he expected, which led him to say, "*I don't understand how to improve my consistency*". Another participant stated that she was not interested in the performance graph and just wanted to play. It seems that the performance graph had mixed opinions among people and it was not clear what the results meant to the participants. Future applications may need to state clearly to users what the knowledge of performance feedback means to the user and its benefits, which could be through an instructional video explaining how to improve their performance. Gamification of the performance results and feedback on progression may be used to motivate people to improve their performance and thus improve their physical ability.

#### *8.4.2.2.2 LEADERBOARD*

There were a few participants that were interested in the leaderboard with these users becoming competitive in the games trying to score the highest points to top the leaderboard. In discussion with these participants, they often said that the competitiveness would sometime translate to the real world, when they met each other, they would become competitive and boast about their scores. On one occasion near the end of the experiment, one participant noticed his previous sessions score had dropped him into second place and were determined to better his score to beat the leader. In Knight Run, he took extra time to navigate through all the paths to collect all the items and kill all enemies to gain as many points as possible. As a result, he topped the leaderboard.

### 8.4.2.3 FETCH

Most of the participants commented on how colourful and beautiful the environment was. The fun physics gave interesting and fun ways to throw the tennis ball at many different heights, angles and distances with some people trying to exploit fetch by trying to throw the ball beyond the maximum boundaries. Fetch was found to be the most boring by all participants and they did not find Fetch to be enjoyable. Four out of the six participants stated that the interactions where too repetitive, one comment made by a participant was "*It's the same thing all the time, it's boring*". Participants did not like that they received no feedback related to the objectives or their progression which seems to have negatively impacted their motivation. It seems that this could have also contributed to the participants' enjoyment during interaction with a participant stating, "*Adding player game statistics might help with boredom*". Most of the participants felt that Fetch was limited in gameplay and suggested numerous ideas to add variety to make it more enjoyable. Two participants mentioned that the time spent in Fetch was too long and would not be suitable for people with stroke. Three participants said that they changed their movement strategy to cope with tiredness by resting their arm on the table between throws (waiting for the dog fetch the ball) and clearer instruction on how to perform the tasks, particularly the use of the pinch gesture to throw the ball are needed. Future use of this game with stroke patients should introduce rest periods between a series of throws to reduce tiredness as stroke patients will tire a lot quicker than non-impaired upper limb users. By the end of the experiment, all participants said they disliked this game over the others.

### 8.4.2.4 CANNON GRAB

Of all six participants, four participants enjoyed Cannon Grab more than any of the other games and VR experiences. It seems the main reason for this was that it provided a challenge to the participant to reach the goal of getting the highest score possible to climb the leaderboard in the Virtual Living Room and beat the other participants. Participants mentioned, "*There is a point to this game*" and "*Seeing a scoreboard is good*" which indicates that participants saw a reason the play which may have motivated them more. Participants did experience some issues with Cannon Grab that affected their experience. One issue was that there no feedback on progression or a goal that participants could work towards on a personal level. For example, maybe show the participants' their previous score to try to beat it. When selecting the cannon balls, they felt almost sticky when attached to the person's fingers and when placing in the barrel they would stick to the edges which the user may have perceived it as a failed attempt causing frustration. Four participants commented that the barrels placed in front of them were too close to their body and the two most front barrels were hard to locate. This could be caused by the incorrect calibration of the table as the position of the barrels is based on the information collected during the calibration process. Another possible issue that may have been a result of the calibration where one participant mentioned "*The high cannon balls where hard to see*" this may be that the participant was overstretching in the RoM task of the calibration, resulting in a RoM space that is larger than the person's normal RoM space.

#### 8.4.2.5 KNIGHT RUN

As mentioned in section 7.3.7.3, Knight Run was considered the most complex for gameplay and interaction with the environment. Knight Run did not include the ability to adapt using Fitts Law, the primary aim for the inclusion of the game in the study was to evaluate the usability and acceptance of a more complex and possible cognitively challenging game. Participants found controlling the character fun and found the adventure theme of the game enjoyable. The objective and scoring system of the game were favourable among all participants with participants mentioning it helped motivate them. An important concern found during the study was that half of the participants experienced some level of motion sickness during play. This is a major concern that would not be suitable for people suffering a stroke and may have negatives effects on the person physically capabilities or may increase other side effects of a stroke. Two of the participants had said their motion sickness had subsided by the next end of the second session. Originally seven participants were recruited, but one participant experienced motion sickness in Knight Run and decided to withdraw from the experiment. Participants expressed that the main reason for the motion sickness was the view, speed, auto adjustments and sudden jerking movements of the camera. All participants found it difficult to control the character when asked to move the cursor on their hand towards their chest, as they were unable to see the direction they should be moving the character, this was due to the positioning of the camera. Some participants said that they had to think a lot more than the other games, with one states "*It requires more thinking, and I think that why I do not feel my arm trying as much*". Although a major concern with this game was motion sickness. If this could be resolved, several participants thought that this game had great potential to become a more enjoyable and fun experience with flexibility for much variety for gameplay.

#### 8.4.2.6 UI INTERACTION

Navigation throughout the RESTEM application requires button interaction to load and exit the games. Interaction with the buttons involves the participant using their virtual hand to collide with the 3D buttons and holding it for a short time, with a loading wheel providing visual feedback. Game loading is achieved through the virtual living room's game selection menu. To exit a game, the user presses a button located on their "impaired arm" with their "less impaired arm". It is expected that this would be easier for people with stroke as the exit game button would be placed on the user's most impaired arm with their healthier arm performing the UI interactions. Selecting the menu buttons was frustrating for some participants who felt that the responsiveness of the button interactions was slow causing multiple failed interaction attempts among participants (Figure 8-21). One of the biggest challenges for menu selection was exiting the games. Some users got frustrated and failed numerous times. Improved responsive collision detection with buttons and other menu interactions is required to improve this, or it is possible that removing hand interaction with menus and implementing a pointer mechanism controlled using the participant head from the VR headset may easily eliminate any unnecessary movement not required by the participant's rehabilitation exercise program.


**Figure 8-21: Example of frustrating button interactions experienced by users**

# 8.5 DISCUSSION

In this chapter, TAGER was enhanced to include games and an adaptive system that could alter task difficulty over time. The evolved system is called RESTEM. An experiment was designed to investigate the embedding of reach and touch tasks, as tested in previous chapters, within games, and to evaluate the effectiveness of the user movement profiler over a longer time. An adaptive system was developed to adapt task difficulty as user performance changed. As it is intended that RESTEM will ultimately be used with stroke patients, its usability was evaluated, and the potential of the games assessed. All participants' except for one completed the whole ten sessions over 5-weeks. The participant that failed to complete the experiment experienced motion sickness in the Knight Run game and did not want to continue. All participants that completed the experiment demonstrated improvement in movement performance from the beginning of the experiment. RESTEM scored a high score on the system usability questionnaire, and all participants expressed high levels of enjoyment while interacting with RESTEM. All participants also preferred wearing the headset and would wear it again, even though it was worn for a substantial amount of time. However, some participants experienced high body temperature while wearing the VR headset. The VR headset did become hot and with the head-mounted Leap Motion Controller also becoming hot which might have contributed to the high temperature. Another contributing factor to the high temperature experienced was that the experiment did occur in the summer with direct sunlight coming through the windows. A cooling fan was introduced and helped regulate the participant's temperature. It may be more suitable for short sessions of VR rehabilitation to prevent discomfort due to heat and also may be beneficial to reduce the Leap Motion Controller temperature, so tracking remains optimal. Future hardware needs to manage the excessive heat better possibly by using a cooling system such as the "Vive N Chill" (James, 2017) that attaches small cooling fans to the headset to cool the users head.

Analysis of the games showed that users favoured mainly the cannon grab game and followed closely by the Knight Run games, all participants found fetch to be boring and repetitive mainly due to the lack of game features to make it fun and interesting. Cannon Grab was more fun for participants due to the gameplay and feedback mechanisms used. Participants experienced some issues with Cannon Grab, mainly after the user had selected the target, the attachment of the target object to the hand seemed unnatural for users. Some users expressed that there was no progression of goals that users could work towards which could negatively impact the level of time they spend playing cannon grab. In Cannon Grab some participants said they found high target objects difficult to select which may have been a result of incorrect calibration of the user RoM, this needs further investigation. Playing the Knight Run game, users felt that the control mechanisms were fun, and the style of game and theme was more interesting to users. However, playing Knight Run caused some participants to experience motion sickness due to the design of the camera's zoom speed being too fast. The lack of smooth dampening of the camera when approaching the camera maximum and minimum movement range and the movement speed of the user's hand was not equal to the speed of movement from the camera causing a disconnect between hand-eye coordination. This type of game would not be suitable for stroke patients unless modification were made to alleviate motion sickness. Some participants stated they had to think about their actions a lot more than the other games; this game may only be less suitable for stroke patients with severe cognitive difficulties. The UI interaction with buttons was frustrating for most participants, and a better UI design would be required to improve accessibility for stroke patients. One such solution may be to use the VR headset as a head pointer to click buttons and navigate through the interface.

Results of the individual user movement profiles over ten sessions were analysed, and it was found that most users' movement performance between the first and fourth sessions were in a learning phase. The more sessions that users took part in, the more the learning effects dissipated with most users plateauing and only showing smaller improvements from then on, as evidenced by more gradual regression line gradients with more sessions. After participants stopped learning, in some cases, movement performance became weaker in some sessions. In these cases, movement profiles showed negative or steeper regression lines gradients, and descriptive statistics demonstrated higher movement time variability from the regression line, which was mainly due to tiredness indicated by user feedback and questionnaires. One participant stated they took a tactical approach to target acquisition by moving fast and not caring about the accuracy of movement, which resulted in a decline in movement performance indicated by a negative regression line gradient, Kurtosis values that shows higher movement times from the regression line suggesting more overshooting. Others moved fast and seemed to fatigue more. The user profile data showed that after the ten sessions all participants improved in their movement performance this corresponds to the user's qualitative results where all participants stated they thought they had improved their performance. As a part of the adaptive system, high-level information could be calculated to give participants feedback on their movement performance at the end of every session. The performance feedback was displayed as a line graph across all sessions that showed values for speed, accuracy and consistency (SAC). The performance feedback had mixed opinions among participants. Some participants failed to understand the components of SAC which resulted in a poorer performance when trying to improve the components of SAC. While others understood enough to express that it influenced the way they played the rehabilitation games which resulted in the users improving their movement performance.

# 8.6 CONCLUSION

A VR rehabilitation gaming system called RESTEM was used with able-bodied users to evaluate its capability to adapt to the user movement over time and assess the usability of RESTEM for future experiments with impaired users. A new algorithm was developed based on the user movement profile developed in previous experiments. The adaptive systems were embedded into new games specifically designed and developed for rehabilitation of the upper limbs following a stroke. Results showed that the adaptive system was capable of adapting the difficulty level of the games over a longer time, with participants showing improvements in movement performance as the system adapts to the right level of difficulty to match the user's movement capacity within the games. The adaptive system was also capable of identifying trends of learning experienced by the users at the beginning of the experiment. It was expected that users would be learning at the beginning of the study and it was evident that the adaptive system could identify this and adapt the difficult between to help speed up the learning process. Participants thought that the adaptive games were highly usable and games that provide gameplay features and feedback on the user's action were reported to be more enjoyable. The continuous use of the VR headset also increased the user enjoyment with the adaptive games.

# 9 CONCLUSIONS AND FUTURE WORK

## 9.1 RESEARCH REFLECTIONS

The research conducted and discussed in this thesis set out to show that rehabilitation games have engaging qualities and that the difficulty of rehabilitation exercises can be adapted to suit the diversity in movement capabilities of each individual stroke patient. The hypothesis set was *that through the use of game-based rehabilitation, novel input technology and the modelling of user movement interactions, a VR rehabilitation solution can be designed to account for each stroke patient's movement capability by adapting and personalising the games, providing a more accessible and enjoyable rehabilitation*.

The objectives of this research were defined in Chapter 1.4 and are stated in brief below:

1) *Literature Review*: Conduct a review of commercial state-of-the-art technologies and rehabilitation in practice, virtual reality-based stroke rehabilitation research, and best practice user interface design.
2) *Design Guidance Framework*: Develop a list of design requirements, constraints from literature, user feedback and collaboration with academics and clinicians.
3) *User Centred System Design and Development*: build a user-centred VR rehabilitation gaming system based on rehabilitation design requirements to personalise gameplay and rehabilitation using adaptive techniques within several adaptive VR rehabilitation games.
4) *User Movement Modelling*: Using data analysis techniques investigate the use of Fitts Law to model user arm movement in reach and touch tasks within the VR user interface.
5) *Usability Evaluation*: Evaluate the usability of the VR system with both healthy and impaired users.

**Objective 1: Literature Review**

A review of the current practices of rehabilitation including the state-of-the-art technologies currently used and researched from VR stroke rehabilitation was conducted. Early research of optical tracking VR rehabilitation devices such as the Eye toy and the GestureTek Gesture Xtreme (GX) system showed promising sign in terms of usability for rehabilitation. However, they were limited in their ability to customise rehabilitation as they were originally for entertainment purposes. Research began into customisable optical tracking technology for rehabilitation with IREX being one of the first to be developed from GX to be customisable for rehabilitation. Optical tracking remains a common tracking technology for rehabilitation systems. More recent developments such as the Microsoft Kinect and the Leap Motion Controller have great potential for adaptive rehabilitation (D. Holmes *et al.*, 2016). A review of the adaptive techniques currently being researched in several experimental systems including Fuzzy Logic, Artificial Neural Networks (ANN), and Fitts Law. Fitts Law was discovered to be a reliable adaptive model for predicting human movement but its use in 3D applications was limited, and the extension of Fitts Law into 3D applications requires more research. It was identified that there was more research needed into adaptive systems as current adaptive techniques were too restrictive focusing on specific areas of moving such as wrist training. It was also evident there was limited research into the use of adaptive systems in a gaming context for rehabilitation. The experiments reviewed of the adaptive systems did not include the latest novel technologies which may have an impact on how adaptive systems perform or how they are designed in future. It was clear from the literature that there was a need to investigate the use of adaptive systems that are embedded into games for rehabilitation and use the latest technologies such as the Leap Motion Controller.

**Objective 2: Design Guidance Framework**

Chapter 3 describes the experimental methodology using a User-Centred Design approach from the PACT framework to gather requirements, constraints, and caveats through various interdisciplinary workshops, visits to hospitals and clinics as well as conducting a series of PPI sessions with stroke patients. The information gathered on VR game design for stroke informed the creation of a novel model for designing an evaluating rehabilitation games, called the Rehabilitation gaming model (RGM) (**Contribution A**). The RGM for designing and evaluating games or gamified solutions incorporates various user types that are motivated in different ways when using gamified application, games design patterns and behaviour techniques are mapped to the user types to design rehabilitation games suited to one or more of the user types in motivating different users and encourage a positive behaviour change toward rehabilitation to increase adherence to their rehabilitation exercises. The RGM was used as an evaluation tool and provided insight into the focus of design for some of the popular existing rehabilitation systems (Holmes *et al.*, 2015; Boureaud *et al.*, 2016).

**Objective 3: User Centred System Design, Development and Testing**

Evolutionary prototypes of a rehabilitation system for reaching and touching exercises were designed and developed called TAGER and later renamed to RESTEM when games and an adaptive difficulty system was added. The design and development of the systems are detailed in chapter 4 and 7 (**Contribution B**). The prototypes evolved using the evolutionary prototyping, a user-centred design approach to developing software applications through the continuous involvement of stakeholders and end-users to receive feedback on the usability of the system. Before the design of a VR rehabilitation system, information gathering was conducted from the existing literature to determine initial requirements for stroke rehabilitation technology. A visit to the Brain Injury Matters was also scheduled in this initial phase, gathering requirements from the clinician and their perception of technology as a possible rehabilitation solution. Findings from these initial stages informed the design of the first version of TAGER, unfortunately at this stage feedback from stroke patients was unable to be obtained due to the considerable time it would take to obtain ethical approval to have permission to communicate with stroke patients. TAGER was evaluated with able-bodied people to assess the usability and perform an analysis of a user profile for modelling user movement based on Fitts Law. Results and feedback from this experiment gave insight into improvements of the quality of the user profile and the user interface of TAGER before experiments with upper limb impaired users. TAGER was also demonstrated to clinicians at the Musgrave Park hospital and a PPI session at the Northern Ireland Chest, Heart and stroke, providing invaluable feedback from stroke patients on improvement to TAGER before experiments with impaired users. Feedback informed several changes to TAGER that helped improve the usability of the system and enhance accessibility. Changes included a calibration stage, along with features towards improving target acquisition for stroke patients. The improved prototype of TAGER was used with upper limb impaired user to evaluate the usability and to analyse the performance of a user movement profiling system to model user movement in the same manner as the previous able-bodied study. Feedback on the system from upper limb impaired participants showed that they see value in the system for rehabilitation purposes. However, it was evident that users were bored and took too long to complete, supporting the need for games to provide a more enjoyable experience. These results emphasized the needed for changes to existing features and the addition of fun games to engage the user; the system was renamed to RESTEM. RESTEM included a comprehensive but fun calibration process and the addition of three games that varied on the level of gameplay and feedback shown to the user. In RESTEM an adaptive algorithm was designed to determine the ability for RESTEM to adapt to user's movement performance over a longitudinal study with able-bodied participants first before future studies with impaired users.

**Objective 4: User Movement Profiling**

In the first study with able-bodied participants, information about the user's movement was recorded, while performing reaching and touching exercises in a 3D virtual space with the novel Leap Motion Controller hand tracking device. A user movement profile was created to model the user's movements. The profile was mainly based on the regression results of Fitts Law including descriptive statistics of the residuals of the regression and other target acquisition performance information that could support finding from the remainder of the profile. The initial profile was described in section 5.4.1.2. Results showed that from the user's profile it was possible to identify when the user had come fatigued or whether the user was still learning the interactions. It was also possible to identify from some participants different behaviours adopted to perform the reaching tasks (**Contribution C(a)**)(Dominic Eugene Holmes *et al.*, 2016). It was also possible to create user movement profiles for different zones in the user's movement space, the results showed it was possible to identify an area of the user's range of movement where they had good and bad movement coordination (**Contribution C(b)**). This has potential benefits for rehabilitation to focus on certain problem areas in stroke patient’s movement. Enhancement of the user motion model was needed before experiments with upper limb impaired users, to help explain more of the user movements that was not clear from the results. The improved user profiler was used in an experiment with upper limb impaired participants. Analysis of the user profiles found that it was possible to identify improvements in movement performance in individual users, despite some participants experiencing tiredness, boredom, and frustration. Like able-bodied participants, it was possible to identify levels of fatigue and if participants were still learning, despite a training session at the start of the experiment. As expected when comparing able-bodied users with impaired users, there was typically a greater diversity of movement exhibited between impaired users (**Contribution C(c)**). On some occasions, it was challenging to model impaired users through regression. However, the regression statistics are still informative and could be used in a different way to adapt the difficulty of the task along with other statistics from the user profile. As a lower number of participants were recruited for the experiment, it may be possible that the result does not fully indicate the limitation of impaired users. Though it would be expected with a larger group of participants it may strengthen the results as well as produce other interesting results. The user profile was used in the third study with able-bodied participants to adapt the difficulty of the tasks over a five-week period, two sessions a week to evaluate the capability of the custom adaptive algorithm to change the difficulty of the task to suit the capabilities of the user's movements. It was found that the adaptive algorithm identified that over a series of sessions, people were still learning (**Contribution D(a)**) but after the users’ learning had diminished the user’s performance began to steadily and slowly improve their performance with more sessions as the system continued to adapt the difficulty in the sessions (**Contribution D(b)**). In some cases, the adaptive system was capable of showing when participants’ movement performance unexpectedly became poor mainly due to tiredness (**Contribution D(a)**). It is also possible that because a low number of participants were recruited for this experiment, it may not indicate the full potential of the adaptive algorithm, more participants may strengthen these results and highlight other interesting results. In future studies with impaired participants, it is possible that higher variation is seen in the adaptive algorithm similar to findings from the comparison between able-bodied and impaired users in previous studies, which may identify other interesting results from the adaptive algorithm. The adaptive system was also designed to calculate and feedback information to the user about their movement performance in a high-level manner known as SAC. SAC expresses to the user their performance regarding speed, accuracy and consistency. The feedback had mixed opinions; some user did not understand how they could improve their movements to positively affect the SAC results, others understood and showed signs of improving SAC thus improving their movement performance (**Contribution D(c)**).

**Objective 5: Usability Evaluation**

In all studies, the usability of the evolutions of the VR rehabilitation prototypes was assessed. User feedback on usability from study 1 and 2 showed that most users had positive views on the usability of the TAGER prototypes. The design of a calibration of the user’s movements was evident from clinician feedback and the prototypes evolved the calibration design throughout the studies to better explain the user’s initial movements capabilities to provide a personalised interaction experience. However, further investigation is required to access the quality of the calibration design (**Contribution E(a)**). In both studies the majority of participants preferred to wear the VR headset as it provided a more enjoyable experience and the from quantitative results it also improved the user's movement performance, with most participants comment that they perceived an improvement in their performance, showing great potential for future use of VR headset in rehabilitation (**Contribution E(b)**). Results on cues with able-bodied participants show promising results, comparing the use of cues against no cues in the VEs showed that using cues resulted in faster movements and a higher number of hits. Cues could be a helpful addition to improving movement performance in users (**Contribution E(c)**). Impaired users did become bored, tired and frustrated over the course of the experiment; this was mainly due to the length of time spent using TAGER was too long. It would be suggested that a future system should be flexible in the amount of time spent performing rehabilitation exercises to reduce bored and tiredness of the user so that engagement can be maintained over multiple session of rehabilitation. The feedback from the two studies emphasised the importance of providing a fun experience which supports the addition of games in rehabilitation. RESTEM included three games for rehabilitation with varying levels of gameplay and feedback. All users preferred the games with more gameplay and feedback. The Fetch game was the most boring because it had no goals, rewards for actions, and was very repetitive. The Knight Run game did induce minor motion sickness and would not be suitable for stroke patients, a redesign of the games navigation features may eliminate motion sickness so that it could be used for a stroke patient. Interaction using the Leap Motion Controller was intuitive and users seemed to enjoy interacting with the games without using a physical controller. However, experience in interacting with menu buttons selection was an issue that caused frustration among some users, a possible solution to button selection is to utilise the VR headset as a pointer for buttons selection. All participants continued to show an increased acceptance of using the VR headset in all studies, as it provided a more enjoyable experience and seemed to improve their movement performance. However, in the third study, the Oculus did seem to contribute to some participants reporting higher body temperature with prolonged use due to the temperature rise of the hardware. the Leap Motion Controller also increased in temperature and as a result the quality of tracking reduced. It would be suitable to have shorter sessions of VR rehabilitation to regulate the user and the hardware temperature for a more comfortable experience until the hardware has improved cooling management (**Contribution E (d & e))**.

# 9.2 FUTURE WORK

The work described in this thesis has been presented and demonstrated at conference events along with demonstrations at a number of clinics, hospitals and PPI sessions. In all cases, the ideas and the design gathered interest from researchers and health professionals that helped validate the design and the approach to creating VR rehabilitation for stroke patients. In its current state, the system requires further development for independent use at clinics and home. To be ready for clinics and at a stroke patient’s home the system requires improvements and additions of features that benefit patients, carers, and physiotherapist and occupational therapist.

Modifications to the current systems to increase accessibility would be to have the application to start every time the user turns on the computer to save time and stop unnecessary actions by the user having to navigate and find the application. Video and images of instructional feedback along with verbal instruction may be useful to instruct the user on how to wear the VR headset safely and for mental rehearsal on how to play each game. Investigation of the calibration is needed to improve the accuracy of the range of movement measure, to ensure when used at home the games can accurately provide comfortable interactions that do not exert the user or encourage incorrect movements. Automatic calibration of the user's environment may also be necessary to ensure that the scale and orientation of the VEs are equally proportionate to the user's height. This will improve the interactions between the user and the virtual objects. For accessibility the user interface is important. Therefore, the interactions with virtual objects using the Leap Motion Controller requires improvement to provide increased natural interaction and reduce frustration experience from some users in the current system.

Continued development of the user model is required to improve the accuracy and possibly indicate other interesting factors that could affect user performance such as cognitive ability. Currently, Fitts Law is calculated in the traditional way, where it calculates the time taken to touch a target form one point (origin) to another point (target). It might be insightful to look at the complete trajectory of the user's hand at intervals between hitting the origin and the target objects, which would give a more accurate representation of the user's natural movement path towards the target object as it may not always be straight to the target for people with upper limb weakness. The trajectory of the movements may also be used to monitor the correctness of movement and provide feedback to the users on how well they are moving.

A useful inclusion to the games would be feedback on progression through the games to show how well they are progressing through the games such as comparing a score from previous gameplay scores or improving the user's ability as they progress (power-ups, boss levels). Achievements are also a good way of showing progression depending on how they are designed but they also reward the player for playing the games and performing certain actions. The addition of achievements would be a good way to further increase the user's engagement in the rehabilitation games thus increase engagement with their rehabilitation exercises. Although the Knight Run game was enjoyable some users experienced motion sickness due to the unsmooth camera following. Providing a fixed camera view similar to the Fetch and Cannon Grab would alleviate motion sickness as in both games no motion sickness was experienced.

The addition of telerehabilitation (Laver *et al.*, 2013) has benefits for patients and healthcare professionals as it allows the healthcare professional to continuously monitor multiple patients remotely and provides a chance to review adherence and exercise performance at home to better understand the patient's condition. It is possible for remote customisation of the games by the health care professional to provide patients with a more personalised rehabilitation experience to suit the patient's need. It may also be useful for remote one to one audio/video chat between patients and their clinician for more regular consultations to review the patient's condition and other problems they may face (Chaponneau *et al.*, 2016).

The flexibility of the current technologies provide increased capabilities for the potential inclusion of multiple therapy types using VR. The system currently includes a form of constraint-induced movement therapy that encourages the use of the impaired arm. However, it is possible for the inclusion of more patients that have very severe upper limb impaired movements by using mirror therapy in VR (McKinney *et al.,* 2018). Traditionally in mirror therapy (Myung Mo, Hwi-young and Chang Ho, 2012; Thieme *et al.*, 2013), the patient is instructed to use the less impaired arm beside a mirror, the reflection in the mirror looks like their most impaired arm. The patient performs rehabilitation exercises while focusing on the reflection of the less impaired arm. In theory, this manipulates the brain to think the person's most impaired arm is performing the exercise, which changes the neuroplasticity of the patient's brain to improve the movement of the patient's most impaired arm without ever moving the impaired arm. We plan in future implementations of the system to include additional types of physical therapy, including mirror therapy.

# 9.3 CONCLUDING REMARKS

The work in this thesis has presented a novel approach to modelling user movements of reaching and touching exercises for the upper limb rehabilitation of stroke users, using a novel natural user interface device called the Leap Motion Controller and the latest Oculus CV1 VR headset. A rehabilitation gaming system was designed through an evolutionary prototyping life-cycle for a user-centred design approach that offers a highly usable system that was effective at modelling and adapting the difficulty of the task based on the user's movement capabilities in real-time over multiple sessions, increasing the accessibility to a wider range of movement capabilities. The usability of the prototypes was evaluated through the research with able-bodied and upper limb impaired participants. The usability of all prototypes remained highly positive among users. However, with an early version of the prototype, the systems were not always fun according to user feedback. Recent versions that included games showed users favoured the games and they provided a more enjoyable experience encouraging more engagement in the games thus, increased adherence to their rehabilitation exercises. The VR Headset also increased the enjoyment of the interaction expressed by a high number of users; the headset also had a positive result on the user movement performance. The research shows potential for providing an adaptive and personalised gaming experience with upper limb impaired users following as stroke or traumatic brain injury. The commercial potential is also promising with the easy to set up and low costing hardware provides an affordable rehabilitation solution. The novel and flexible interfacing devices show potential for use with a higher diversity of upper limb impairments which make it suitable for both the clinic and at home.

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# 11 APPENDICES

# APPENDIX A. A DETAILED OUTLINE OF THE RGM MODEL

| Gamification User Type: Achiever | | |
|---|---|---|
| Reward/Reputation System | Game Design Patterns | Behaviour Change Techniques Taxonomy |
| Challenges | Alignment, Deadly Traps, Enemies, Evade, Guard, Limited Resources, Maneuvering, Obstacles, Overcome, Player Killing, Puzzle Solving, Race, Rescue, Time Limits | Problem Solving, Graded tasks |
| Certificates | Competence Areas, Game Mastery, Producers | |
| Quests | Collection, Committed Goals, Continuous Goals, Dynamic Goal Characteristics, Ephemeral Goals, Excluding Goals, Goal Points, Hierarchy of Goals, Incompatible Goals, Interferable Goals, King of the Hill, Mutual Goals, Near Miss Indicators, Optional Goals, Predefined Goals, Selectable Sets of Goals, Supporting Goals, Symmetric Goals, Unknown Goals, Conceal, Configuration, Connection, Delivery, Traverse | Goal Setting(behaviour + outcome) |
| Learning/New Skills | Achilles' Heels, Character Development, Experimenting, Gain Competence, Gain Information, Handicaps, Memorizing, New Abilities, Perceived Chance to Succeed, Power-Ups, Privileged Abilities, Reconnaissance, Role Reversal, Skills, Symmetry | Problem Solving, Instruction on how to perform a behaviour, Demonstration of the behaviour, Associative Learning, Behavioural practice/rehearsal |
| Boss Battles | Boss Monsters, Higher-Level Closures as Gameplay Progresses | |
| Levels/ Progression | Diminishing Returns, Improved Abilities, Levels, Obstacles, Producers, Red Queen Dilemmas, Resources, Score, Skills, Smooth Learning Curves, Higher-Level Closures as Gameplay Progresses | Behavioural practice/rehearsal, Remove punishment |

| Gamification User Type: Disruptor | | |
|---|---|---|
| Reward/Reputation System | Game Design Patterns | Behaviour Change Techniques Taxonomy |
| Anarchy | Betrayal, Player Elimination | |
| Light Touch | Bluffing, Damage, Limited Planning Ability, Paper-Rock-Scissors, Randomness, Red Herrings, Role Reversal, Secret Alliances, Uncertainty of Information | |
| Anonymity | Asymmetric Information, Bluffing, Cards, Fog of War, Handles, Paper-Rock-Scissors, Role Reversal, Secret Alliances, Stealth | |
| Development Tools | Constructive Play, Planned Character Development, Tools | |
| Voting/Voice | Betrayal | Information about others approval |
| Innovation Platform | Player Constructed Worlds, Player Decided Results, Player Defined Goals, Player-Decided Distribution of Rewards & Penalties, Reconfigurable Game World | |

| Gamification User Type: Free Spirit | | |
|---|---|---|
| Reward/Reputation System | Game Design Patterns | Behaviour Change Techniques Taxonomy |
| Exploration | Area Control, Exploration, Game State Overview, Maneuvering, Movement, Movement Limitations, Privileged Movement, Traces, Controllers, Imperfect Information, Inaccessible Areas | |
| Branching Choices | Analysis Paralysis, Asymmetric Goals, Attention Swapping, Betrayal, Cognitive Immersion, Freedom of Choice, Illusion of Influence, Limited Set of Actions, Planned Character Development, Risk/Reward, Roleplaying, Stimulated Planning, Tradeoffs | |

| | | |
|---|---|---|
| Easter Eggs | Pick-Ups, Resource Locations, Secret Resources, Easter Eggs | Material Incentive(behaviour), Material reward(behaviour) |
| Unlockable/ Rare Content | Progress Indicators, Resource Generators, Rewards, Surprises, Ultra-Powerful Events | |
| Customisation | Camping, Characters, Construction, Player Defined Goals, Player Constructed Worlds, Player-Decided Distribution of Rewards & Penalties, Reconfigurable Game World | Restructuring the physical environment |
| Creativity Tools | Creative Control, Empowerment, Player Constructed Worlds, Player Decided Results, Player Defined Goals, Player-Decided Distribution of Rewards & Penalties | Restructuring the physical environment |

| Gamification User Type: Philanthropist | | |
|---|---|---|
| Reward/Reputation System | Game Design Patterns | Behaviour Change Techniques Taxonomy |
| Access | Asymmetric Goals, Buttons, Chargers, Tools, Controllers | |
| Meaning/Purpose | Identification, Perceived Chance to Succeed | |
| Care-taking | Helpers, Safe Havens, Tension, Tied Results, Mule | Social Support(un-specified), Social Support(practical), Social Support(emotional) |
| Collect & Trade | Bidding, Collecting, Contact, Converters, Enclosure, Gain Ownership, Negotiation, Pick-Ups, Reconnaissance, Safe Havens, Tools, Tradeoffs, Trading | |
| Sharing Knowledge | Cooperation | Social Support(un-specified), Social Support(emotional), Identification of self as role model |
| Gifting/Sharing | Cards, Cooperation, Card Hands | Social Support(un-specified), Social Support(practical) |

| Gamification User Type: Player | | |
|---|---|---|
| Reward/Reputation System | Game Design Patterns | Behaviour Change Techniques Taxonomy |
| Points/ Exp Points (XP) | Budgeted Action Points, Characters, Consumers, Container, Outcome Indicators, Score | Cue Signaling rewards, Material Incentive(behaviour),Self-reward, Reward (outcome) |
| Physical Rewards/Prizes | Chargers, Illusionary Rewards, Individual Rewards, Non-Renewable Resources, Pick-Ups, Player Decided Distribution of Rewards & Penalties, Power-Ups, Renewable Resources, Resource Generators, Resource Locations, Resources, Rewards, Secret | Cue Signaling rewards, Material Incentive(behaviour), Material reward(behaviour), Non-specific reward(include positive reinforcement), Social reward, Social incentive, Non-specific incentive, Self-incentive, Incentive(outcome), Self-reward, Reward (outcome), Reward |

| | | |
|---|---|---|
| | Resources, Symmetric Resource Distribution | approximation, Reward completion, Situation specific reward, Reward incompatible behaviour, Reward alternative behaviour |
| Leaderboards/Ladders | High Score Lists, Red Queen Dilemmas, Tiebreakers | Self-monitoring of behavior, Self-monitoring of outcome(s) of behaviour, Social comparison |
| Badges/Achievements | Characters, Ownership, Producers | Graded Tasks |
| Virtual Economy | Arithmetic Rewards for Investments, Budgeted Action Points, Consumers, Container, Geometric Rewards for Investments, Investments, Limited Resources, Ownership, Pick-Ups, Renewable Resources, Resource Locations, Rewards | Cue signaling rewards, Material Incentive(behaviour), Material reward(behaviour), Incentive(outcome), Self-reward, Reward (outcome) |
| Lottery/Game of Chance | Betting, Leaps of Faith, Luck | |

| **Gamification User Type: Socializer** | | |
|---|---|---|
| Reward/Reputation System | Game Design Patterns | Behaviour Change Techniques Taxonomy |
| Social Status | Handles, High Score Lists, Individual Penalties, Individual Rewards, King of the Hill, Near Miss Indicators, Privileged Abilities, Privileged Movement, Public Information, Red Queen Dilemmas, Shared Penalties, Shared Resources, Shared Rewards, Social Statuses, Status Indicators | Social comparison |
| Social Network | Alliances, Asynchronous Games, Collaborative Actions, Communication Channels, Indirect Information, Individual Penalties, Interferable Goals, Last Man Standing, Multiplayer Games, Near Miss Indicators, Negotiation, Public Information, Secret Alliances, Social Dilemmas, Social Interaction, | Social Support(un-specified), Social Support(practical), Social Support(emotional) |

| | | |
|---|---|---|
| | Spectators, Symmetric Information, Tiebreakers, Tied Results, Uncommitted Alliances, Synchronous Games | |
| Social Pressure | Betrayal, Uncommitted Alliances | Information about others approval |
| Competition | Agents, Balancing Effects, Capture, Combat, Competition, Conflict, Early Elimination, Eliminate, Last Man Standing, Multiplayer Games, Paper-Rock-Scissors, Player Killing, Race, Time Limits, Tournaments, Transfer of Control, Varied Gameplay | |
| Social Discovery | Communication Channels, Social Organizations | |
| Guilds/Teams | Agents, Alliances, Betrayal, Collaborative Actions, Dynamic Alliances, Multiplayer Games, Player Decided Results, Secret Alliances, Shared Penalties, Shared Resources, Shared Rewards, Social Interaction, Social Organizations, Symmetric Information, Symmetric Resource Distribution, Team Balance, Team Development, Team Elimination, Team Play, Tiebreakers, Tied Results, Tournaments, Varied Gameplay | Social Support(un-specified) Social Support(practical), Social Support(emotional) |

# APPENDIX B. STUDY 1: INCLUSION AND DEMOGRAPHIC PRE-QUESTIONNAIRE

1. What age are you?__________
2. What is your gender?
3. Which type of games do you play? (tick all that apply):
   - ☐ Crosswords or puzzles
   - ☐ Board Games
   - ☐ Casual games (e.g. Words with Friends, Candy Crush)
   - ☐ Hand held games (mobile, 3DS, PS Vita)
   - ☐ 3D games on consoles or computer (PC, Mac, Xbox, PS4, WiiU)
   - ☐ None
4. How often do you play games?
   - ☐ Once a day
   - ☐ Once a week
   - ☐ Once a month
   - ☐ Rarely
   - ☐ Never
   - ☐ Other (Please state below)

   ______________________________________________

5. Have you ever played a game with PS Eye, Kinect or Leap cameras? Yes/No
6. Please tell us your dominant hand.
   - ☐ Left handed
   - ☐ Right handed
7. How often do you use a computer in a week?
   - ☐ Less than 1 hour
   - ☐ 1 to 5 hours
   - ☐ 5 to 15 hours
   - ☐ 15 to 40 hours

☐ Greater than 40 hours

8. Which pointing device do you use with your computer?

   ☐ Mouse

   ☐ Trackball

   ☐ Trackpad

   ☐ Trackpoint

   ☐ Joystick

   ☐ Other

Inclusion Criteria Questions

1. Are you currently taking part in any other research for your condition? ☐ ☐
   Yes No

2. Do you have any depth perception vision issues? Eg do you find it hard to determine the distance between two objects in three dimensions (3D) ☐ ☐
   Yes No

3. Do you have any vision issues when using a computer screen? e.g. colour distortion, light sensitivity, blurred vision etc. Yes ☐ No ☐

   If yes please state your vision issue(s):

   ________________________________________

   ________________________________________

   ________________________________________

4. Do you have any physical disability or arthritis that restricts movement of the neck, shoulders, arms or hands? Yes ☐ No ☐

   If yes please state the condition(s):

   ________________________________________

   ________________________________________

   ________________________________________

5. Any other comments?

   ________________________________________

   ________________________________________

# APPENDIX C. STUDY 1: CONSENT FORM

Research Participant Consent Form

**Title of Project:** User Modelling for Adaptive and Personalised Physical Therapy in Rehabilitation games.

Name of Chief Investigator: Dr. Darryl Charles

Please Initial

- I confirm I have been given and have read and understood the information sheet for the above study and have asked and received answers to any questions raised. [ ]

[ ]

- I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason and without my rights being affected in any way. [ ]

- I understand that the researchers will hold all information and data collected securely and in confidence and that all efforts will be made to ensure that I cannot be identified as a participant in the study (except as might be required [ ]

[ ]

| | | |
|---|---|---|
| Name of Subject | Signature | Date |
| Name of person taking consent | Signature | Date |
| Name of Chief Investigator | Signature | Date |

# APPENDIX D. STUDY 1: INFORMATION SHEET

Research Participant Information Sheet

**Title of Project:** User Modelling for Adaptive and Personalised Physical Therapy in Rehabilitation games.

Thank you for your interest in participating in this study the contents of this document will explain what this research aims to achieve and what you are required to do, if you decide to participate. Please read the information given and ask any question you may have about the study before you agree to participate.

This study is being conducted in partial fulfilment of the requirements for the Degree of Doctor of philosophy (Ph.D) at the University of Ulster Coleraine.

What is the purpose of the study?

This study is part of a research project looking at how virtual reality or games can be designed in such a way that they incorporate physiotherapy exercise targeted at people with impairment in the upper limbs due to a neurological condition. Research has shown that many people become bored of their usual exercise program and this hinders their progress to improve their motor skills. Games are widely known as a highly engaging form of entertainment, so adapting a game to include exercise for upper limbs could eliminate boredom and encourage physiotherapy exercise. This study is the initial research stage trying to find out information that could be helpful in the way we design such a virtual reality or game. This study tracks the participant’s upper limbs and monitors the interactions within a 3D world using a small desk mounted infrared camera called the Leap Motion. Information recorded will be used to measure a number of different factors such as difficulty of interaction and fatigue.

Why are you being asked to take part?

In this study we wish to record motion data of people with no impairment in their upper limbs. This study will be used later to compare with impaired individuals to find the margin of capabilities. This will help visualise the difference in the capabilities and help in adapting future interventions to those impaired in the upper limbs.

Do you have to take part?

Participation in this study is completely voluntary. If you decide to take part, you can change your mind at any time and withdraw from the study without giving any explanation or notice.

What will happen if you decide to take part?

If you decide to take part in the study you will be asked to give written consent for your upper limbs to be tracked and data recorded and stored securely. Once consent is given and any questions you have are answered you will be asked to attend the University of Ulster Coleraine on one occasion for approximately 30 minutes. During this time you will be required to interact with a 3D environment on a computer, selecting objects within the 3D environment. Your upper limb movements will be recorded as well as any objects you may interact with in the 3D environment. You will be asked to perform 10 slightly different tasks. Data will be stored securely at the University of Ulster and will be used to aid in the development of future virtual reality or gaming software for those impaired in the upper limb region.

What will you be asked to do?

You will be asked to perform 10 slightly different tasks; each task should take a short period of time with a break between most tasks of 15 seconds to rest your upper limbs. Tasks may be repeated if data has not been recorded. In each task you will be using the same way of interaction throughout the 3D world. You will move you upper limbs toward virtual 3D objects and by pointing and touching them you select the object.

Are there any disadvantages or risks to taking part?

There are no major risks associated with taking part. The tasks require you to elevate your upper limbs over the Leap Motion for a short time and could cause discomfort and tiredness in the upper limbs. For this reason, between most tasks the participant is given a rest period ensuring discomfort and fatigue is limited.

What if something goes wrong?

This study is designed to be non-invasive therefore is in unlikely that any issues could arise that would result in harm or discomfort to the participant.

What will happen when the study ends?

The gathered data will be used to aid in the future development of computer software particularly virtual reality and games that are targeted towards those with impaired upper limbs. No personal information will be require from the participant so only the data recorded from the computer software will be stored securely in a password protected and encrypted laptop until the end of the research project.

After the research ends the data will be stored securely in the School of Computing and Information Engineering in accordance with the university's research governance guidelines. The data may be used in publications or presentations relating to the research project and may also be used in future research.

Who is organising or funding this research?

This study is organised by the University of Ulster as part of a research project which is supported by the Department for Employment and Learning, Northern Ireland.

Who has reviewed the study?

This study has undergone a peer review by a member of the academic staff at the University of Ulster Coleraine and is not involved in the study. This person is sufficiently knowledgeable to make an informed judgement of the appropriateness and quality of this study. This study has also been reviewed by the Faculty of Computing & Engineering Ethics Committee to ensure the study meets the university's research governance requirements. For further details see the Research Governance section of the University's website at research.ulster.ac.uk/rg.

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# APPENDIX E. STUDY 1: POST-QUESTIONS ON USABILITY OF SEMI-STRUCTURED INTERVIEWS

1. Did you notice any difference in your performance of the course of the experiment?
2. Did you find any difficulties using the system?
3. Can you describe your experience with the VR headset and the PC Monitor?
4. Did you experience any fatigue during the experiment?
5. Did the visual cues affects your performance and how?
6. Did the tactile cues affects your performance and how?
7. Did the audio cues affects your performance and how?

# APPENDIX F. STUDY 2: ORECNI ETHICS COMMITTEE REPORT

HSC Business Services Organisation

Office for Research Ethics Committees Northern Ireland (ORECNI)
Customer Care & Performance Directorate
Lissue Industrial Estate West
Rathdown Walk
Moira Road
Lisburn
BT28 2RF
HSC REC A
10 November 2016

Dr Darryl Charles
Ulster University, School of Computing and Information Engineering
Room L134, Cromore Road
Coleraine
BT52 1SA

Dear Dr Charles

| | |
|---|---|
| Study title: | User Modelling for Adaptive and Personalised Physical Therapy in Rehabilitation games. |
| REC reference: | 16/NI/0112 |
| Protocol number: | 16/0050 |
| Amendment number: | Amendment 1: 13/10/2016 |
| Amendment date: | 17 October 2016 |
| IRAS project ID: | 204230 |

The above amendment was reviewed at the meeting of the Sub-Committee held on 09 November 2016 in correspondence.

Ethical opinion

The members of the Committee taking part in the review gave a **favourable ethical opinion** of the amendment on the basis described in the notice of amendment form and supporting documentation.

| | |
|---|---|
| 16/NI/0112: | Please quote this number on all correspondence |

Yours sincerely

Kathryn Taylor.

pp Mrs Celia Diver-Hall Alternate Vice-Chair – Chair of the meeting

E-mail: RECA@hscni.net

# APPENDIX G. STUDY 2: DEMOGRAPHIC AND INCLUSION QUESTIONNAIRE

1. What age are you?__________
2. What is your gender?
3. What date did your injury occur? ______________________
4. What arm was affected from your injury? Left ☐ Right ☐ Both ☐
5. Which type of games do you play? (tick all that apply):

   ☐ Crosswords or puzzles

   ☐ Board Games

   ☐ Casual games (e.g. Words with Friends, Candy Crush)

   ☐ Hand held games (mobile, 3DS, PS Vita)

   ☐ 3D games on consoles or computer (PC, Mac, Xbox, PS4, WiiU)

   ☐ None
6. How often do you play games?

   ☐ Once a day

   ☐ Once a week

   ☐ Once a month

   ☐ Rarely

   ☐ Never

   ☐ Other (Please state below)

   ____________________________________________________________
7. Have you ever played a game with PS Eye, Kinect or Leap cameras? Yes/No
8. Please tell us your dominant hand.

   ☐ Left handed

   ☐ Right handed
9. How often do you use a computer in a week?

   ☐ Less than 1 hour

   ☐ 1 to 5 hours

   ☐ 5 to 15 hours

- ☐ 15 to 40 hours
- ☐ Greater than 40 hours

10. Which pointing device do you use with your computer?

- ☐ Mouse
- ☐ Trackball
- ☐ Trackpad
- ☐ Trackpoint
- ☐ Joystick
- ☐ Other

Inclusion Criteria Questions

6. Are you currently taking part in any other research for your condition? ☐ ☐
   Yes No

7. Do you have any depth perception vision issues? Eg do you find it hard to determine the distance between two objects in three dimensions (3D) ☐ ☐
   Yes No

8. Do you have any vision issues when using a computer screen? e.g. colour distortion, light sensitivity, blurred vision etc. Yes ☐ No ☐

   If yes please state your vision issue(s):
   ______________________________
   ______________________________
   ______________________________

9. Do you have any physical disability or arthritis that restricts movement of the neck, shoulders, arms or hands? Yes ☐ No ☐

   If yes please state the condition(s):
   ______________________________
   ______________________________
   ______________________________

10. Any other comments?
    ______________________________
    ______________________________

# APPENDIX H. STUDY 2: CONSENT FORM

Research Participant Consent Form

**Title of Project:** User Modelling for Adaptive and Personalised Physical Therapy in Rehabilitation games.

Name of Chief Investigator: Dr. Darryl Charles

Please Initial

- I confirm I have been given and have read and understood the information sheet for the above study and have asked and received answers to any questions raised. [ ]

[ ]

- I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason and without my rights being affected in any way. [ ]

- I understand that the researchers will hold all information and data collected securely and in confidence and that all efforts will be made to ensure that I cannot be identified as a participant in the study (except as might be required by law) and I give my permission for the researchers to hold relevant data. [ ]

[ ]

[ ]

| | | |
|---|---|---|
| Name of Subject | Signature | Date |
| Name of person taking consent | Signature | Date |
| Name of Chief Investigator | Signature | Date |

# APPENDIX I. STUDY 2: INFORMATION SHEET

Simplified Research Participant Information Sheet

**Title of Project:** User Modelling for Adaptive and Personalised Physical Therapy in Rehabilitation games.

Thank you for your interest in participating in this study the contents of this document will explain what this research aims to achieve and what you are required to do. Please read the information given and ask any question you may have about the study before you agree to participate.

This study is being conducted in partial fulfilment of the requirements for the Degree of Doctor of philosophy (Ph.D) at the Ulster University Coleraine.

What is the purpose of the study?

This study is part of a research project looking at how virtual reality or games can be designed in such a way that they incorporate physiotherapy exercise targeted at people with impairment in the upper limbs. Research has shown that many people become bored of their usual exercise program hindering improve in motor skills. Games are widely known as a highly engaging form of entertainment, so adapting a game to include exercise for upper limbs could eliminate boredom and encourage physiotherapy exercise.

Why are you being asked to take part?

In this study we wish to record motion data of people with limited movement in their upper limbs. This study will be used to compare the data with previous studies data recorded from healthy people with full control of their upper limbs. From this comparison we can determine difference in interaction performance and capabilities, using this comparison it can help in adapting interfaces suited to individual impaired people.

Do you have to take part?

Participation in this study is completely voluntary; you can change your mind at any time and withdraw from the study without explanation or notice.

What will happen if you decide to take part?

If you decide to take part in the study you will be asked to give written consent for your upper limbs to be tracked and data recorded and stored securely. Once consent is given and any questions you have are answered you will be asked to attend the Brain injury matters clinic on one occasion. During this time you will be required to interact with a 3D environment on a computer, selecting objects within the 3D environment.

What will you be asked to do?

You will be asked to perform 10 slightly different tasks; each task should take a short period of time with a break between most tasks of 15 seconds to rest your upper limbs. Tasks may be repeated if data has not been recorded. You will move you upper limbs toward virtual 3D objects and by pointing and touching them you select the object.

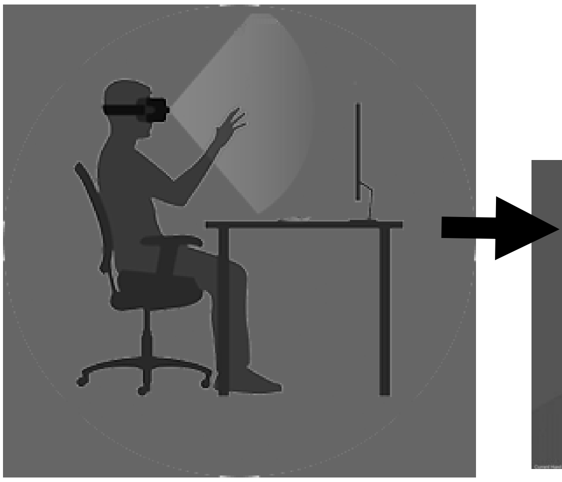

**Figure 1: Perform movements while wearing a VR headset with**

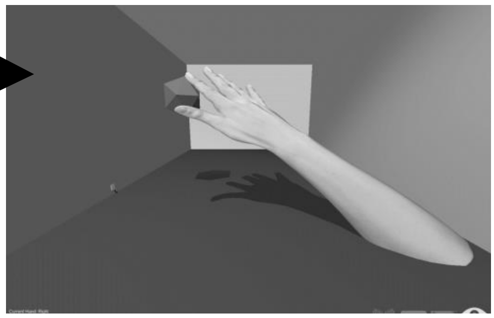

**Figure 2: Your movements copied inside the computer game.**

Are there any disadvantages or risks to taking part?

There are no major risks associated with taking part. If discomfort is felt at any point during the study they are free to withdraw from the study.

What if something goes wrong?

This study is designed to be non-invasive therefore is in unlikely that any issues could arise that would result in harm or discomfort to the participant.

What will happen when the study ends?

When the study ends you will not be contacted or expected to take part in any further research. The gathered data will be used to aid in the future development of computer software particularly virtual reality and games that are targeted towards those with impaired upper limbs. Only the data recorded from the computer software will be stored securely in a password protected and encrypted laptop until the end of the research project. The data may be used in publications or presentations relating to the research project and may also be used in future research.

Who is organising or funding this research?

This study is organised by the Ulster University as part of a research project which is supported by the Department for Employment and Learning, Northern Ireland.

Who has reviewed the study?

This study has undergone a peer review by a member of the academic staff at the Ulster University Coleraine and is not involved in the study. This person is sufficiently knowledgeable to make an informed judgement of the appropriateness and quality of this study. This study has also been reviewed by the Faculty of Computing & Engineering Ethics Committee to ensure the study meets the university's research governance requirements. For further details see the Research Governance section of the University's website at research.ulster.ac.uk/rg.

For further information please contact:

# APPENDIX J. STUDY 2: POST-QUESTIONNAIRE ON USABILITY

1. How would you rate your performance when you first started interacting in the application?

| **Bad 1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **Good 10** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

2. How would you rate your performance when you finished interacting with the application?

| **Bad 1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **Good 10** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

3. When wearing the oculus did you feel your performance changed? select one answer below

   A. ☐ Improved (go to Q4)
   B. ☐ Stayed the same (go to Q6)
   C. ☐ Worsened (go to Q5)

4. If you selected "**Improved**" above can you rate to what degree did your performance improved?

**Accuracy**

| Improved 1 | 2 | 3 | 4 | Improved Vastly 5 |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

Speed

| Improved 1 | 2 | 3 | 4 | Improved Vastly 5 |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

5. If you selected “**Worsened**” above can you rate to what degree did your performance declined?

**Accuracy**

| Declined 1 | 2 | 3 | 4 | Declined Vastly 5 |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

Speed

| Declined 1 | 2 | 3 | 4 | Declined Vastly 5 |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

6. Please indicate the impact the following had on you performance?
   A. When target changed colour.

**Accuracy**

| Improved Vastly | Improved Slightly | No Change | Declined Slightly | Declined Vastly |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

Speed

| Improved Vastly | Improved Slightly | No Change | Declined Slightly | Declined Vastly |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

   B. When vibration on the arm occurred.

**Accuracy**

| Improved Vastly | Improved Slightly | No Change | Declined Slightly | Declined Vastly |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

Speed

| Improved Vastly | Improved Slightly | No Change | Declined Slightly | Declined Vastly |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

C. When Shadows of hand and targets where visible

| **Accuracy** | | | | |
|---|---|---|---|---|
| Improved Vastly | Improved Slightly | No Change | Declined Slightly | Declined Vastly |
| ☐ | ☐ | ☐ | ☐ | ☐ |
| Speed | | | | |
| Improved Vastly | Improved Slightly | No Change | Declined Slightly | Declined Vastly |
| ☐ | ☐ | ☐ | ☐ | ☐ |

7. Did you feel that you began to tire over the course of the tasks? ☐
   Yes ☐ No
8. Did you become frustrated at any point? Please rate frustration below. ☐
   Yes No ☐

| **Frustrated 1** | **2** | **3** | **4** | **Vastly Frustrated 5** |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

Please comment why you became frustrated.

______________________________________________________________

______________________________________________________________

_____________________________________

9. Did you find the tasks boring? Yes ☐ No ☐

| Boring | | | | Vastly Boring |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| ☐ | ☐ | ☐ | ☐ | ☐ |

10. What would you suggest to make it more interesting?

____________________________________________________________

____________________________________________________________

____________________________________

____________________________________________________________

__________________

11. Please state any other comments you have below that was not covered above?

____________________________________________________________

____________________________________________________________

____________________________________________________________

____________________________________________________

# APPENDIX K. STUDY 3: DEMOGRAPHIC AND INCLUSION QUESTIONNAIRE

9. What age are you?__________
10. What is your gender? ☐ Male ☐ Female ☐ Other
11. Which type of games do you play? (tick all that apply):
    - ☐ Crosswords or puzzles
    - ☐ Board Games
    - ☐ Casual games (e.g. Words with Friends, Candy Crush)
    - ☐ Hand held games (mobile, 3DS, PS Vita)
    - ☐ 3D games on consoles or computer (PC, Mac, Xbox, PS4, WiiU)
    - ☐ None
12. How often do you play games?
    - ☐ Once a day
    - ☐ Once a week
    - ☐ Once a month
    - ☐ Rarely
    - ☐ Never
    - ☐ Other _________________________
13. Have you ever played a game with PS Eye, Kinect or Leap cameras? Yes/No
14. Please tell us your dominant hand.
    - ☐ Left handed
    - ☐ Right handed
15. How often do you use a computer in a week?
    - ☐ Less than 1 hour
    - ☐ 1 to 5 hours
    - ☐ 5 to 15 hours
    - ☐ 15 to 40 hours
    - ☐ Greater than 40 hours

16. Which pointing device do you use with your computer?

    ☐ Mouse

    ☐ Trackball

    ☐ Trackpad

    ☐ Trackpoint

    ☐ Joystick

    ☐ Other _____________

Inclusion Criteria Questions

11. Are you currently taking part in any other research for your condition? ☐ Yes ☐ No

12. Do you have any depth perception vision issues? Eg do you find it hard to determine the distance between two objects in three dimensions ☐ Yes ☐ No

13. Do you have any vision issues when using a computer screen? e.g. colour distortion, light sensitivity, blurred vision etc. ☐ Yes ☐ No

    If yes please state your vision issue(s):

    ______________________________________________

    ______________________________________________

    ______________________________________________

14. Do you have any physical disability or arthritis that restricts movement of the neck, shoulders, arms or hands? ☐ Yes ☐ No

    If yes please state the condition(s):

    ______________________________________________

    ______________________________________________

    ______________________________________________

15. Any other comments?

    ______________________________________________

    ______________________________________________

    ______________________________________________

# APPENDIX L. STUDY 3: CONSENT FORM

Research Participant Consent Form

**Title of Project:** User Modelling for Adaptive and Personalised Physical Therapy in Rehabilitation games.

Name of Chief Investigator: Dr. Darryl Charles

Please Initial

- I confirm I have been given and have read and understood the information sheet for the above study and have asked and received answers to any questions raised. [ ]

[ ]

- I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason and without my rights being affected in any way. [ ]

- I understand that the researchers will hold all information and data collected securely and in confidence and that all efforts will be made to ensure that I cannot be identified as a participant in the study (except as might be required by law) and I give my permission for the researchers to hold relevant data. [ ] [ ] [ ] [ ]

| | | |
|---|---|---|
| Name of Subject | Signature | Date |
| Name of person taking consent | Signature | Date |
| Name of Chief Investigator | Signature | Date |

# APPENDIX M. STUDY 3: INFORMATION SHEET

Research Participant Information Sheet

**Title of Project:** User Modelling for Adaptive and Personalised Physical Therapy in Rehabilitation games.

Thank you for your interest in taking part in this study the contents of this document will explain what this research aims to achieve and what you are required to do, if you decide to take part. Please read the information given and ask any questions you may have about the study before you agree to participate.

This study is being conducted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy (PhD) at the Ulster University Coleraine.

What is the purpose of the study?

This study is part of a research project looking at how virtual reality or games can be designed in such a way that they include physiotherapy exercise targeted at people with impairment in the upper limbs. Research has shown that many people become bored of their usual exercise program and this hinders their progress to improve their motor skills. Games are widely known as a fun form of entertainment, so changing a game to include exercise for upper limbs could stop boredom and encourage physiotherapy exercise. This study is the trying to find out information that could be helpful in the way we design such a virtual reality or game.

Why are you being asked to take part?

In this study, we wish to record motion of people with limited movement in their upper limbs. This study will be used to assess the system's reliability and accuracy to adapt to each individual's motor skills. This study will help us inform future developments needed that may raise concern for people with impairments in their upper limbs as well as be used as a comparison between people with healthy upper limbs and people who have impaired upper limbs.

Do you have to take part?

Participation in this study is completely voluntary. If you decide to take part, you can change your mind at any time and withdraw from the study without giving any explanation or notice.

What will happen if you decide to take part?

If you decide to take part in the study you will be asked to give written consent. Once consent is given and any questions you have are answered you will be asked to attend the Ulster University, Cromore Road, Coleraine, BT52 1SA on 12 occasions. During this time you will be required to play with 3D virtual reality tasks on a computer. Your motions will be recorded while performing these tasks.

What will you be asked to do?

You will be asked to perform a number of different tasks; each task should take a short period of time with a break between the tasks to rest your upper limbs. In each task, you will be using the same way of interaction throughout the 3D world. You will move your upper limbs toward virtual 3D objects and by reaching and touching the object. After all tasks are completed you will be given a short questionnaire on your experience of the tasks. You will be required to participate in 12 sessions, 30mins per session giving a total of 6 hours participation. You may be asked to repeat a session in the unlikely event that the data was not successfully collected. While you participate videos and picture may record you this is to help us analysis movement and gather feedback from your sessions.

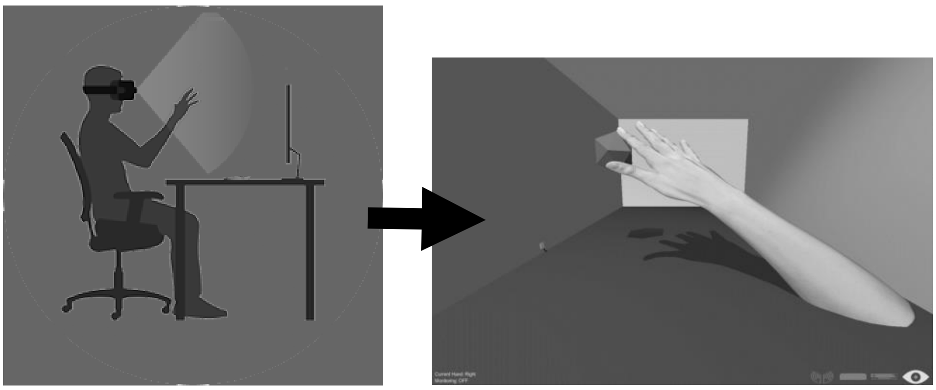

**Figure 1: Perform movements while wearing a VR headset with leap motion camera attached.**

**Figure 2: Example of Your movements copied inside the Virtual Reality.**

Are there any disadvantages or risks to taking part?

There are no major risks associated with taking part. The tasks require you to elevate your upper limbs towards the Leap Motion (camera) for a short time and could cause discomfort and tiredness in the upper limbs. For this reason, between the tasks you are given a rest period ensuring discomfort and tiredness is limited. If discomfort is felt at any point during the study you are free to withdraw from the study.

What if something goes wrong?

This study is designed to be as safe as possible therefore is unlikely that any issues could arise that would result in harm or discomfort to you.

What will happen when the study ends?

The results will be used to aid in the future development of computer software particularly virtual reality and games that are targeted towards people with impaired upper limbs.  No personal information will be required from you so only the data recorded from the computer software and questionnaire will be stored securely in a password protected and secure laptop until the end of the research project.

After the study ends the results will be stored securely in the School of Computing and Information Engineering in accordance with the university's research governance guidelines. The results may be used in publications or presentations relating to the research project and may also be used in future research.

For further information please contact:

# APPENDIX N. STUDY 3: POST-QUESTIONNAIRE ON USABILITY

1. How would you rate your performance when you first started interacting in the application?

| Bad<br>1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Good<br>10 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

2. How would you rate your performance when you finished interacting with the application?

| Bad<br>1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Good<br>10 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

3. How easy was it for you to accomplish the tasks when you began this current session?

| Bad<br>1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Good<br>10 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

4. Since your previous session, how easy was it to remember the tasks you had to perform?

| Bad<br>1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Good<br>10 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

5. How enjoyable do you think the system is to use?

| Bad<br>1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Good<br>10 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |

6. Did you find the VR headset enjoyable to use?

Yes ☐ No ☐

7. If Yes to question 8 would you continue to wear it?

Yes ☐ No ☐

8. Did you feel that you began to tire over the course of the tasks?

Yes ☐ No ☐

| Tired<br>1 | 2 | 3 | 4 | Extremely Tired<br>5 |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

9. Did you become frustrated at any point? Please rate frustration below.

Yes ☐ No ☐

| Frustrated<br>1 | 2 | 3 | 4 | Extremely Frustrated<br>5 |
|---|---|---|---|---|
| ☐ | ☐ | ☐ | ☐ | ☐ |

Please comment why you became frustrated.

____________________________________________________________

____________________________________________________________

____________________________________

10. Did you find the tasks boring? Yes ☐ No ☐

| Boring | | | | Extremely boring |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| ☐ | ☐ | ☐ | ☐ | ☐ |

11. What would you suggest to make it more interesting?

______________________________________________

______________________________________________

___________________________

12. Please state any other comments you have below that was not covered above?

______________________________________________

______________________________________________

______________________________________________

_________________________________________

# APPENDIX O. SYSTEM USABILITY SCALE

Participant ID: _______________________Date:_______

System Usability Scale

**Instructions:** For each of the following statements, mark one box that best describes your reactions to the system *today*.

| | | Strongly Disagree | Disagree | Don't Know | Agree | Strongly Agree |
|---|---|---|---|---|---|---|
| 1 | I think that I would like to use this system frequently. | | | | | |
| 2 | I found this system unnecessarily complex. | | | | | |
| 3 | I thought this system was easy to use. | | | | | |
| 4 | I think that I would need assistance to be able to use this system. | | | | | |
| 5 | I found the various functions in this system were well integrated. | | | | | |
| 6 | I thought there was too much inconsistency in this system. | | | | | |
| 7 | I would imagine that most people would learn to use this system very quickly. | | | | | |
| 8 | I found this system very cumbersome/awkward to use. | | | | | |
| 9 | I felt very confident using this system. | | | | | |
| 10 | I needed to learn a lot of things before I could get going with this system. | | | | | |

# APPENDIX P. STUDY 1: ALL PARTICIPANTS USER MOVEMENT PROFILES OVER TIME

| User | 1001 | 1002 | 1004 | 1005 | 1006 | 1007 |
|---|---|---|---|---|---|---|
| Start Descriptive | | | | | | |
| Standard Deviation | 0.945 | 0.634 | 0.465 | 0.424 | 0.566 | 0.594 |
| Kurtosis | 9.380 | -0.116 | 2.217 | 0.139 | 9.488 | 6.794 |
| Skewness | 2.594 | 0.659 | 1.421 | 0.806 | 2.477 | 2.174 |
| End Descriptive | | | | | | |
| Standard Deviation | 0.290 | 0.395 | 0.553 | 0.446 | 0.693 | 0.469 |
| Kurtosis | 11.205 | 1.756 | 6.189 | 4.109 | 16.857 | 2.765 |
| Skewness | 2.905 | 1.419 | 2.214 | 1.795 | 3.366 | 1.572 |
| Start Regression | | | | | | |
| $R^2$ | 0.027 | 0.180 | 0.345 | 0.089 | 0.055 | 0.092 |
| P-Value | 3.3E-01 | 1.9E-02 | 2.2E-10 | 2.8E-02 | 2.5E-01 | 1.2E-02 |
| Intercept (a) | 0.420 | 0.218 | -0.376 | 0.182 | 0.552 | 0.403 |
| Slope (b) | 0.513 | 0.208 | 0.583 | 0.451 | 0.442 | 0.567 |
| Sin coefficient (c) | -0.170 | 1.320 | 0.743 | -0.122 | -0.480 | -0.101 |
| End Regression | | | | | | |
| $R^2$ | 0.121 | 0.027 | 0.022 | 0.018 | 0.014 | 0.106 |
| P-Value | 6.0E-03 | 4.3E-01 | 3.1E-01 | 4.6E-01 | 6.7E-01 | 4.6E-03 |
| Intercept (a) | 0.326 | 1.405 | 0.525 | 0.581 | 1.101 | 0.385 |
| Slope (b) | 0.150 | -0.280 | 0.309 | 0.227 | 0.153 | 0.430 |
| Sin coefficient (c) | 0.295 | 0.370 | -0.155 | -0.120 | -0.456 | 0.030 |
| Performance | | | | | | |
| Targets Hit (1080) | 896 | 634 | 927 | 799 | 708 | 909 |
| Start Hits | 83 | 43 | 101 | 80 | 52 | 94 |
| End Hits | 82 | 63 | 94 | 90 | 59 | 99 |
| % Change Hits | -1.20% | 46.51% | -6.93% | 12.50% | 13.46% | 5.32% |
| Start Mean Time | 1.505 | 1.477 | 1.342 | 1.167 | 1.309 | 1.638 |
| End Mean Time | 0.856 | 0.978 | 1.080 | 1.036 | 1.206 | 1.358 |
| % Change Mean Time | -43.15% | -33.80% | -19.50% | -11.23% | -7.85% | -17.05% |
| User | | | | | | |
| Age | 20 | 20 | 19 | 24 | 22 | 30 |
| Gender | F | F | F | M | F | F |

| User | 1008 | 1009 | 1010 | 1011 | 1012 | 1013 |
|---|---|---|---|---|---|---|
| Start Descriptive | | | | | | |
| Standard Deviation | 0.455 | 0.304 | 0.340 | 0.508 | 0.485 | 0.828 |
| Kurtosis | 3.182 | 3.114 | 0.014 | 4.422 | 0.268 | 25.581 |
| Skewness | 1.223 | 1.535 | 0.884 | 1.791 | 1.001 | 4.186 |
| End Descriptive | | | | | | |
| Standard Deviation | 0.527 | 0.330 | 0.340 | 0.844 | 0.907 | 0.368 |
| Kurtosis | 3.097 | 2.133 | 3.067 | 18.483 | 26.216 | 6.545 |
| Skewness | 1.326 | 1.558 | 1.718 | 3.603 | 4.425 | 1.834 |
| Start Regression | | | | | | |
| $R^2$ | 0.265 | 0.216 | 0.133 | 0.090 | 0.054 | 0.215 |
| P-Value | 5.3E-04 | 8.4E-06 | 1.1E-03 | 4.4E-02 | 2.2E-01 | 1.0E-03 |
| Intercept (a) | 0.409 | 0.182 | 0.325 | 0.412 | 0.086 | -0.355 |
| Slope (b) | 1.016 | 0.387 | 0.311 | 0.294 | 0.521 | 0.695 |
| Sin coefficient (c) | -2.083 | 0.099 | 0.139 | 0.316 | -0.197 | 0.792 |
| End Regression | | | | | | |
| $R^2$ | 0.206 | 0.214 | 0.149 | 0.077 | 0.012 | 0.352 |
| P-Value | 4.4E-04 | 1.6E-05 | 8.9E-04 | 8.2E-02 | 6.4E-01 | 2.2E-06 |
| Intercept (a) | 0.238 | 0.431 | 0.265 | -0.243 | 0.750 | -0.099 |
| Slope (b) | 0.291 | 0.102 | 0.171 | 0.949 | 0.180 | 0.477 |
| Sin coefficient (c) | 0.868 | 0.696 | 0.484 | -1.130 | 0.288 | 0.598 |
| Performance | | | | | | |
| Targets Hit (1080) | 732 | 926 | 918 | 767 | 740 | 698 |
| Start Hits | 52 | 99 | 98 | 69 | 58 | 60 |
| End Hits | 70 | 95 | 90 | 65 | 80 | 63 |
| % Change Hits | 34.62% | -4.04% | -8.16% | -5.80% | 37.93% | 5.00% |
| Start Mean Time | 1.461 | 1.095 | 1.106 | 1.294 | 1.217 | 1.695 |
| End Mean Time | 1.435 | 1.049 | 0.947 | 1.307 | 1.354 | 1.352 |
| % Change Mean Time | -1.82% | -4.20% | -14.43% | 1.02% | 11.33% | -20.27% |
| User | | | | | | |
| Age | 26 | 42 | 22 | 37 | 44 | 24 |
| Gender | F | M | F | F | F | M |

| **User** | **1014** | **1015** | **1016** | **1017** | **1019** | **1020** |
|---|---|---|---|---|---|---|
| Start Descriptive | | | | | | |
| Standard Deviation | 0.649 | 0.262 | 1.087 | 0.402 | 0.447 | 0.375 |
| Kurtosis | 2.411 | 4.480 | 7.662 | 1.625 | 2.469 | 0.694 |
| Skewness | 1.135 | 2.115 | 2.394 | 1.173 | 1.454 | 1.199 |
| End Descriptive | | | | | | |
| Standard Deviation | 0.649 | 0.272 | 0.543 | 0.548 | 0.519 | 0.716 |
| Kurtosis | 2.411 | 5.947 | 10.630 | 17.637 | 1.013 | 66.273 |
| Skewness | 1.135 | 2.476 | 2.482 | 3.080 | 1.099 | 7.260 |
| Start Regression | | | | | | |
| $R^2$ | 0.088 | 0.102 | 0.029 | 0.303 | 0.289 | 0.225 |
| P-Value | 5.0E-02 | 5.4E-03 | 2.7E-01 | 8.6E-08 | 8.5E-07 | 3.8E-06 |
| Intercept (a) | 0.542 | 0.226 | 0.865 | 0.252 | -0.509 | 0.169 |
| Slope (b) | 0.806 | 0.286 | 0.324 | 0.145 | 0.817 | 0.510 |
| Sin coefficient (c) | -1.162 | -0.039 | 0.507 | 1.146 | 0.103 | 0.211 |
| End Regression | | | | | | |
| $R^2$ | 0.036 | 0.105 | 0.168 | 0.084 | 0.324 | 0.131 |
| P-Value | 2.7E-01 | 4.7E-03 | 2.3E-04 | 1.2E-02 | 1.0E-08 | 8.3E-04 |
| Intercept (a) | 1.431 | 0.180 | 0.577 | 0.673 | -0.743 | -0.418 |
| Slope (b) | -0.097 | 0.304 | 0.062 | 0.072 | 1.305 | 0.677 |
| Sin coefficient (c) | -0.241 | -0.098 | 1.127 | 0.748 | -0.976 | 0.360 |
| Performance | | | | | | |
| Targets Hit (1080) | 661 | 959 | 976 | 964 | 909 | 981 |
| Start Hits | 68 | 100 | 92 | 93 | 85 | 101 |
| End Hits | 73 | 99 | 94 | 103 | 97 | 104 |
| % Change Hits | 7.35% | -1.00% | 2.17% | 10.75% | 14.12% | 2.97% |
| Start Mean Time | 1.704 | 0.856 | 1.914 | 1.292 | 1.500 | 1.429 |
| End Mean Time | 1.053 | 0.831 | 1.386 | 1.269 | 1.713 | 1.272 |
| % Change Mean Time | -38.16% | -2.95% | -27.57% | -1.80% | 14.25% | -10.97% |
| User | | | | | | |
| Age | 30 | 26 | 31 | 50 | 66 | 56 |
| Gender | M | M | M | M | F | M |

| User | 1021 | 1022 | 1023 | 1025 | 1026 | 1020 |
|---|---|---|---|---|---|---|
| Start Descriptive | | | | | | |
| Standard Deviation | 0.426 | 0.643 | 0.583 | 0.559 | 0.622 | 0.375 |
| Kurtosis | 2.794 | -0.358 | 2.881 | 2.441 | 1.269 | 0.694 |
| Skewness | 1.678 | 0.612 | 1.387 | 1.423 | 1.213 | 1.199 |
| End Descriptive | | | | | | |
| Standard Deviation | 0.267 | 0.670 | 0.425 | 0.564 | 0.411 | 0.716 |
| Kurtosis | 12.366 | 0.994 | 3.461 | 3.694 | 0.827 | 66.273 |
| Skewness | 3.070 | 1.068 | 1.589 | 1.533 | 1.173 | 7.260 |
| Start Regression | | | | | | |
| $R^2$ | 0.198 | 0.068 | 0.219 | 0.198 | 0.133 | 0.225 |
| P-Value | 1.9E-05 | 1.2E-01 | 6.3E-06 | 6.1E-05 | 1.1E-03 | 3.8E-06 |
| Intercept (a) | -0.021 | 0.728 | -0.409 | -0.276 | -0.073 | 0.169 |
| Slope (b) | 0.337 | 0.298 | 0.795 | 0.852 | 0.393 | 0.510 |
| Sin coefficient (c) | 0.578 | 0.396 | 0.446 | -0.106 | 0.715 | 0.211 |
| End Regression | | | | | | |
| $R^2$ | 0.070 | 0.136 | 0.379 | 0.185 | 0.078 | 0.131 |
| P-Value | 3.2E-02 | 6.9E-03 | 9.5E-11 | 6.8E-05 | 3.2E-02 | 8.3E-04 |
| Intercept (a) | 0.453 | 0.931 | -0.645 | 0.034 | 0.274 | -0.418 |
| Slope (b) | 0.121 | -0.160 | 0.790 | 0.712 | 0.435 | 0.677 |
| Sin coefficient (c) | 0.173 | 1.656 | 0.461 | -0.006 | -0.528 | 0.360 |
| Performance | | | | | | |
| Targets Hit (1080) | 983 | 687 | 1000 | 963 | 913 | 981 |
| Start Hits | 102 | 63 | 100 | 91 | 98 | 101 |
| End Hits | 98 | 71 | 100 | 97 | 88 | 104 |
| % Change Hits | -3.92% | 12.70% | 0.00% | 6.59% | -10.20% | 2.97% |
| Start Mean Time | 1.076 | 1.662 | 1.645 | 1.561 | 1.262 | 1.429 |
| End Mean Time | 0.832 | 1.529 | 1.375 | 1.609 | 0.957 | 1.272 |
| % Change Mean Time | -22.60% | -8.02% | -16.38% | 3.07% | -24.19% | -10.97% |
| User | | | | | | |
| Age | 44 | 46 | 54 | 67 | 24 | 56 |
| Gender | M | F | F | M | F | M |

# APPENDIX Q. INITIAL INTERDISCIPLINARY WORKSHOP

**ULSTER UNIVERSITY**

**Faculty of Computing and Engineering**

**Minutes of meeting**

*(This form should be completed by the research student after each meeting and subsequently approved by the supervisor/s)*

| | | | |
|---|---|---|---|
| **Student:** | Dominic Holmes | **Date / Time:** | 19th Jan 2015 2pm |
| **Supervisors:** | Dr Darryl Charles, Prof Philip Morrow, Prof Sally McClean | **Location:** | Ulster University |
| **Present at meeting:** | Dr Darryl Charles, Dr Suzanne McDonough, Sarah Howes and Dominic Holmes | **Duration:** | 2 Hours |

**Issues discussed *(please itemise and provide brief details):***

Virtual reality can offer the motivation for practising specific actions at the intensity required to induce cortical reorganisation. Most systems provide knowledge of the result (i.e. whether or not the outcome was successful), although there is the potential for knowledge of performance (i.e. details of the effectiveness of a movement, for example, through provision of kinematic feedback). Tasks can be graded by clinicians to provide a progressively challenging practice that can be performed without direct clinical supervision (Pollack et al, 2014). Laver (2011) reviewed the evidence for VR and showed that more than 15 hours of VR led to a better outcome than less than 15 hours of VR therapy (60 mins x 15 sessions; could be 3 times/week or no specified how regular). This review included 12 trials that involved 397 participants for the upper limb and concluded that the use of virtual reality and interactive video gaming may be beneficial in improving upper limb function and ADL function when used as an adjunct to usual care (to increase overall therapy time) or when compared with the same dose of conventional therapy. Of the 12 trials only one trial investigated the effect of commercial gaming console, but 7 investigated commercially available VR systems-eye toy, Kinect, IREX; effects were seen for subacute stroke only (less than 6 months). There was insufficient evidence to reach conclusions about the effect of virtual reality and interactive video gaming on grip strength, gait speed or global motor function. It is unclear at present which characteristics of virtual reality are most important and it is unknown whether effects are sustained in the longer term. Intervention approaches in the included studies were predominantly designed to improve motor function rather than cognitive function or activity performance. The majority of participants were relatively young and more than one-year post stroke.

This review also concluded that

1) Researchers and manufacturers designing new virtual reality programs for rehabilitation purposes should include the use of pilot studies assessing usability and validity as part of the development process. This is an important part of the development process and should be conducted with the intended users of the program (see chapter at end of references-might be worth buying access to this; Levin et al, 2015-mentions Fitts law).

2) One of the key potential advantages of using virtual reality programs is that they could be used without the need for direct therapist supervision. For example, they could be used alone in the home environment or in a group setting with supervision from therapy aids as a way of increasing therapy dose without increasing staffing. There are few research studies that have examined virtual reality interventions in this way, yet this is one of the most desirable characteristics of this approach.

**Social dynamic**

- Group work has proven successful in the past
- Groups of the same age could potential have a better social dynamic therefore better support for each other when in rehabilitation eg a 15 - 19-year-old group has better social interactions than with a wider age range.
- Groups can help bring out individuals' personalities, increase confidence, better motivation etc.

**Game design**

- Feedback is important for such as tactile, visual and audio cues
- Some patients with neglect of their affected side need active prompts to attend to the side with neglect. The most typical feature of unilateral neglect (UN), following stroke, is failure to report or respond to stimuli presented from the contralateral space, including visual, somatosensory, auditory, and kinesthetic sources. The reported incidence varies from 10 to 82% following right- and from 15 to 65% following left-hemisphere stroke (Yang et al, 2013). Unilateral left neglect, a lack of responses to the left side of space, is one of the best single predictors of poor functional recovery following stroke and is difficult to rehabilitate. In the last 30 years, various rehabilitation approaches have attempted to improve the recovery of patients with chronic and persistent unilateral neglect. These approaches can be divided into two classes: rehabilitation procedures based on top-down mechanisms (require patients to be aware of their deficit and to have the capacity to voluntarily maintain attention oriented to the affected field) and those based on bottom-up mechanisms (do not require the patient to be aware of their difficulty-approaches include sensory stimulation (vestibular, optokinetic, left-sided transcutaneous mechanical vibration, left-sided electrical nervous stimulation and left-limb proprioceptive stimulation) to enhance the contralesional space; Frassinetti et al, 2002). In a recent systematic review rehabilitation was classified under two types of behavioural (bottom up) approaches: recruiting the hemiplegic limbs to reduce spatial preference for the ipsilesional space, or improving awareness of the contralesional space to promote patients' attention (Yang et al, 2013). Yang et al (2013) concluded that there is modest evidence for the use of prism adaptation (see Frassinetti et al, 2002 for an example of this intervention) to reduce UN in stroke, with immediate and long-lasting effects, and eye patching (hemiplegic half-field eye patching works by blocking the ipsilesional visual field) for immediate effects. Other studies obtained positive effects from the use of visual scanning training (Ferreira et al., 2011), visuomotor feedback (Harvey et al., 2003), and Transcranial brain stimulation (Koch et al., 2012). It would be very useful to consider whether any of these options could be integrated into the virtual environment?

- The better the patient becomes at performance in game reduce the amount of cues given to provide a more complex and difficult task. Would be good to define what cues we could give in the VE and how we would judge that their performance has improved-in UN studies they use line cancellation tests etc as outcomes.
- Variation in activity is important for engagement and to target specific muscle groups.
- Enable games to encourage bilateral movement and potentially some basic bimanual movements. Simultaneous bilateral arm training uses activities for which both arms perform identical movements at the same time. Different forms of simultaneous bilateral arm training are available. Some use 'free' arm movements, and others use mechanical or robotic devices to drive active or passive movement of the affected limb through identical movement of the less-affected upper limb. The key ingredient of this form of intervention is interlimb coupling, which is thought to rebalance interhemispheric inhibition, activate the affected hemisphere and improve motor control within the affected limb (Pollock et al, 2014). It is of note that Pollock et al (2014) conclude that there may be moderate level evidence that unilateral training is more effective for rehab of upper limb function than bilateral training-so although we could include bilateral training-the focus might be better on unilateral training.

- Need repetitive task training which involves the repeated practice of functional tasks (whole task practice when possible), combining elements of intensity of practice and functional relevance (French 2007). Repetitive task training—when progressed appropriately—is thought to reduce muscle weakness and to form the physiological basis of motor learning (Butefisch 1995). Key components of skill acquisition, such as active cognitive involvement, functional relevance of the task and knowledge of results and performance, are hypothesised to enhance learning during repetitive task training (Schmidt 2014). These components are central to the so-called 'movement science' approach to stroke rehabilitation (Carr 1987; Carr 1990; Carr 1998). Findings from animal research have shown that neuroplastic changes emerge only after new skills are learned—not after repetitive movement (Nudo 2000; Nudo 2003a; Nudo 2003b). Hence, it is important to emphasise that the 'repetition' within repetitive task training refers to repeated practice of new functional skills—not to the reproduction of identical movements per se-cut and pasted from Pollock et al (2014). Repetitve task training may augment the activity of neural pathways that underlie specific functions and promote acquisition of the tasks practised, and may increase muscle strength and endurance (Pollack, 2014). Note that in Pollock review it is only those studies that had repetitive task training for more than 20 hours (over the course of the intervention based on 3 small trials) that showed an effect-so need to design our system with this in mind.
- Stretching and positioning are important. Several techniques may be used to optimise joint position and to maintain or regain soft tissue length. These techniques often involve the use of assistive devices, such as supportive devices, splints and orthoses. Shoulder subluxation has traditionally been treated with supportive devices (Ada 2005). Splints are external devices used to fix a joint in one position, often used to support the hand or fingers in an optimal position. Orthoses are external devices (similar to splints) applied to elbow, wrist and/or finger joints to optimise position, provide stability and prevent, limit or assist movement (Hoffman 2011; Lannin 2007). These may be used alone or with electrical stimulation in a neuroprosthesis (an orthotic device with prepositioned electrodes that assist function) (Hendricks 2001)-. cut and pasted from Pollock et al (2014). Stretching can reduce muscle stiffness and help maintain range of movement (Pollack, 2014). In the Pollack review there is moderate level

evidence of no benefit or harm from stretching for upper limb impairment and ADL.

- For difficulty consider proximity adjustments, reducing proximity towards target to make it more difficult. See Levin (2015) which makes reference to Fitts law and which Dominic is testing as part of his PhD.

**Exercises in game**

- Reach to grasp is a good example of task specific training which is a common part of rehabilitation following stroke. Task-specific training, also referred to as functional task training, involves practice of tasks relevant to daily life, including part- and whole-task practice (Pollack et al, 2014). Grasp functionality is easier for people with stroke to obtain and is one of the first things that is learnt so most patients already know this. It may not be worth using the grasp exercise and also it tends not to be used by the patient a lot. Some patients can grasp but are unable to extend their wrist at the same time so would be good if we could identify if a patient was extending their wrist and see below, rotating their wrist so that the forearm is midway between supination (wrist facing the ground) and pronation (wrist facing upwards).
- Active Daily Living (ADL) focuses on extension and rotation of wrist e.g. buttoning a shirt button requires extension of the wrist and rotation for the hand to face the button, as well as elbow flexion and correct positioning of the shoulder.
- Reach is also important in ADL
- Important to avoid movements that causes spasticity or contractive issues.
- Repetition reduces spasticity.
- 60s breaks are sufficient anything over this can cause patient to become less interested.

**MYO Armband**

- Could be potentially used to detect wrist extension
- If the Myo could tell the difference between extensor and flexor muscles this would help identify if the correct exercises are performed.
- Extensor muscles at the wrist (which could be measured below the elbow joint with the myo) indicate correct movements towards improved functional movement of the wrist and forearm i.e. elbow flexion and pronation and wrist extension.
- If Myo can only monitor gross muscle movement of all muscles around the elbow joint (I.e. both extensor and flexor muscles) it may not prove useful in rehabilitation.

**Fatigue**

- A noisy or drop in signal of the Myo's EMG data could indicate fatigue.
- When patients fatigue on a specific muscle group e.g. shoulder, the patient doesn't have to stop a change in activity focused on a different muscle group is better than stopping to let the fatigued muscle recover again.

- Patients struggle to adjust to real environment outside of rehabilitation, consider real time manipulation and slowing down real time to allow manipulation then increase to real time to help them adapt to the real environment scenarios.

**Actions / further work *(please itemise and provide brief details):***

- Using these suggestions and other research develop a rehabilitation system
- Investigate the Myo Armband further to get more detailed knowledge to determine its usefulness for rehabilitation.

# APPENDIX R. SECOND INTERDISCIPLINARY WORKSHOP

## Day at Brian Injury Matter Clinic

**Date:** 2nd Sept 2016 **Time:** 2pm **Duration:** 2 hours

**Attendees:** Dominic Holmes **Location:** Brian Injury Matters, Belfast

Dr Katy Pedlow

Dr Darryl Charles

Prof Suzanne McDonough

**Issues discussed (please itemise and provide brief details):**

**VR system (TAGER)**

- After Katy played with the system she found it easy to use. She particularly was pleased with how responsive and accurate the tracking of the hands were.
- She liked the hand model saying it gave a more realistic feel compared to Ka Shek research that in some cases you couldn't recognise it as a hand.
- After experimenting with the calibration at the beginning to replicate more severe mobility issues, she though this could allow more of her patients to take part.
- Calibration needs an to account for users reach length for more comfortable interaction
- The target acquisition should be timed so any users that find it difficult to select a target the user should be allowed to move on to the next target if they can't select the current target.
- The Myo Armband may me difficult for users to put on themselves so will need assistance.
- The participants may have low muscle mass so the Myo may not be able read any information from the user.
- The Oculus is very light which it may have been a concern when wearing for long periods. Sickness was another issue but after demoing, Katy thought it may not be as big an issue as she thought this is the same for epilepsy.

**Recruitment**

- Katy thinks that she would be able to recruit more patients than she originally thought.
- Katy offered to print all recruitment documents and give them to potential participants.
- Katy will perform the Motorcity Index to determine the inclusion criteria.

- She also mentioned that if any volunteers are needed she could maybe get some to help out.

**Other issues**

- Access to the patients from an external organisation needs permission. Katy will look into this mentioning that it shouldn't take long (approx. 2 days) to do this.

**Actions Needed**

- Dominic to send all recruitment documentation and estimated date of start the study to Katy Pedlow.
- Dominic to make modification to the rehab system
- Katy Pedlow will ensure access is granted to Dominic in order to start the study with her Patients.

# APPENDIX S. THIRD INTERDISCIPLINARY WORKSHOP

## Minutes of meetings

**Date:** 17th May 2017 **Time:** 10am **Duration:** 2hours

**Attendees:** Dominic Holmes **Location:** Net Coms, Ulster University Coleraine

Suzanne McDonough

Darryl Charles

Philip Morrow

Sally McClean

**Issues discussed (please itemise and provide brief details):**

**Ethics**

- If study takes place in a hospital the consultant may need to be the chief Investigator (CI). Not sure if a CHS consultant will need to be a CI, we will need find this out.
- Another important factor that may determine the study period for each person is the amount of time they are at the hospital or clinic.
- We want to get video and imaging consent for this study.
- Must screen participants to meet a cognitive threshold.

**Recruitment**

- Potential recruitment from Katy's Group, chest heart and stroke (CHS) or Musgrave hospital.
- Advantage of using Katy's group is that pre-assessment can be done in advance before visiting, CHS may be able to do this in advance as well but we will have to ask.
- Chatted about bring the participants to the university but this would be more difficult for the participants to travel and they wouldn't be in there natural setting because environmental factors may be important.
- A Large number of participants may be hard to get and also keeping participant may also be difficult for a longer period study. We will try to recruit as many as possible with recruitment being in parallel with multiple systems setup or staggered recruitment depending on the participants and clinics availability to take part.

**Design Feedback of current system**

- Calibration is very important testing user motion every time they login to the game and changing the movement space may help improve engagement- if the participant can play within their own movement space they are more likely to have more a successful performance with good results, giving incentive to play more often. System usability – related to player engagement with the participant having their own movement space mapped, the ability to complete challenges in that space becomes easier.

- Should be designed in such a way that the games tap into the participant's competitive nature. The RGM and player types could help here.
- Knowledge of performance is important but determining how to show this to the participants could be difficult. Keeping it simple and clear is important as participants can ignore because they don't understand it or it is too complex.
- Maybe have clinical tasks and as a reward participants get to play games.
- Having a reminder system may also be important to educate and motivate participants (e.g. remember to drink water).
- Subjective measure- allow participants to express their feelings by self-selecting from questions can help adapt the systems difficulty.
- Rest period are very important greater than 60secs can cause the participant to lose interest (this needs to be carefully considered).
- Music choice may be important fast music can speed you up and vice versa. Controlling the tempo of the music may help; depending on what skill the patient has to focus on. For example, focusing on accuracy- slow music may be more appropriate, speed may involve higher tempo music.

**Analysis**

- How do we measure the long-term usability? – The models (adaptive algorithm) ability to smoothly adapt to the user's motions, based on previous performances and emotional aspects (e.g. are they tired today).
- Sector analysis is novel and potentially more accurate for each participate. If the model can identify areas of concern based on performance in certain areas of the user's movement space, we can decide what happens. Is it due to fatigue? -consider giving them a break or temporally move the space closer to the user to continue playing. Is it constantly happening? - focus more on this area as it could be an area of concern. Another aspect to consider when deciding what to do, is the direction of the movement. Is arm movement across the body? If so this is usually harder may consider a different adapting approach.
- Specific limb kinematic is very interested but difficult to determine if specific rehab exercises are being perform correctly. Simple limb kinematic is possible such as body leaning, arm extension, wrist orientation (when selecting objects).

**Actions Needed**

- Suzanne to contact Musgrave park hospital as a potential recruitment location and to ask if a consultant must the CI for the study.
- Dominic- To continue writing up ethics.

# APPENDIX T. PPI SESSION AT NORTHERN IRELAND CHEST HEART AND STROKE

## Northern Ireland Chest Heart and Stroke (NICHS) Demo Day

So, we went to the NICHS centre in Belfast to demonstrated the latest in Virtual Reality equipment and our latest research for stroke rehabilitation. The technology was demonstrated to clinicians and stroke volunteers. The stroke volunteers where given a questionnaire to complete, below are the accumulated answers to each question.

1. Have you used commercial gaming systems for fun, if so can you name the systems.
    A. NO
    B. IPad for solitaire (very computer literate).
    C. NO
    D. Playstation with Son.
    E. Wii, Playstation (couldn't master not because od stroke) played with son in the past rally games.
    F. Xbox- Call of duty, fifa. Unable to used the Playtstation controller.
    G. NO
    H. BCX
    I. Wii – like bowling game was her favourite, spectrum Atari and xbox( hasn't played these since stroke).

2. Have you used commercial gaming systems as part of rehabilitation?
    A. NO
    B. NO
    C. NO
    D. NO
    E. NO
    F. Using xbox helped with recovery of Left hand, Wii in hospital – upper limb tennis.
    G. NO
    H. Stepped using following a stroke. Felgbdt she was unable to use it
    I. Games as part of rehab – for hard ??? -bask- ??? wood in Cardiff

3. What did you like/dislike about these systems; what else is needed?

   A. N/A
   B. N/A
   C. N/A
   D. Afraid of systems because of dizziness + balance problems.
   E. Liked Dominic's game with different levels to complete the task, saw others as paly things,
   F. LIKE- Something different, DISLIKE- needs to be more specific to rehabilitation.
   G. N/A
   H. Fun Element, Competition
   I. Liked all of them – liked being in the rooms turn to real life scenarios into virtual physio worlds, disliked – hard to follow on your own and need to simplify commercial games.

4. Do you have a mobile phone? What Type? Do you game on your phone?
   A. Yes – no games use it one handed as other hand is unused with phone.
   B. Nothing specified
   C. Nothing specified
   D. Yes – tried Pokemon using Iphone
   E. IPhone, Ipad- solitaire/ scrabble/ chess – cognitive
   F. Iphone pokemon go – get you out, can also use it in the car.
   G. Nothing specified
   H. Samsung touch screen
   I. Iphone 6 scrabble game, cognitive word game training with friends , squash the bubbles game, decided to do these games herself with advice given from friends
5. Have you used or thought about some type of physical activity tracker (e.g. steps on your phone etc.)?
   A. Nothing specified
   B. Nothing specified
   C. Nothing specified
   D. Not at the moment but interested.
   E. Map my ride, map my walk used for heart condition to monitor activity was quiet motivating and rewarding.
   F. Would not use it as not active enough to warrant expense
   G. Nothing specified
   H. Uses apps on phone daily, sets step target @10,000 in cycling mode when cycling
   I. Fitbit but hasn't set it up yet needs help setting it up.
6. Do you use social media? What type? For what main reason?
   A. Would like to use Facebook – doesn't like public forums
   B. Nothing specified
   C. Nothing specified
   D. Facebook
   E. Facebook, twitter

F. Facebook (mentioned its his addiction) to keep in touch + find out what going on in the world. Uses snapchat for a laugh
G. Nothing specified
H. Interact with family and friends, immediately after stroke felt the social media was useful to remain in contact with the world.
I. Facebook/ twitter and would be open to a virtual world

7. Are you getting formal rehabilitation?
   A. Had private for one month or once a month??
   B. Nothing specified
   C. Nothing specified
   D. None
   E. No
   F. Not since 2012, 6 month in RABILI + 2 month outpatients then community stroke team for few sessions d/c
   G. Nothing specified
   H. Unsure of acute rehab (brief on words), community stroke team (again brief) – current residual Paw and stiffness in affected shoulder, reduced isolation & fear of going outside
   I. Physio- Rebound clinic for function in Left legand range of movement in ankle to improve walking.
8. Have you a home based exercise programme? If yes, what helps or stops you from doing it? What would help you do more?
   A. Nothing specified
   B. Nothing specified
   C. Nothing specified
   D. Prep @ home / volunteers now – finished Jam /fes, Can't use bike because of dizziness.
   E. Playing 18 holes of golf has problems with score card and has given up keeping score for himself.
   F. Forget exercises, helpful to have review sessions to remember exercises.
   G. Nothing specified
   H. Feels its not personalised, prefers hands on therapy felt it helped a lot better rather than generic exercises
   I. Walk the dog + physio frame in rebound.
9. What else could our system help with?
   A. Nothing specified
   B. Nothing specified
   C. Nothing specified
   D. ???
   E. Cognitive side of things
   F. Nothing specified
   G. Nothing specified
   H. Less conscious of paw & stiffness in VR world felt she could move it more. Reduce fear of activities such as making a cup of tea.

I. Use virtual world to train + teach carers etc

10. Have you any other comments?

A. Nothing specified
B. Nothing specified
C. Nothing specified
D. Nothing Specified
E. Nothing Specified
F. Simulation of effects of stroke.
G. Nothing specified
H. Feasibility in real life (setting up etc) handling a cup etc for first time, practising certain movements.

# APPENDIX U. PPI SESSION AT STROKE ASSOCIATION, ENNISKILLEN

## Stroke Association Demo Day

So we went to the Stroke Association centre in Enniskillen where demonstrated the latest in Virtual Reality equipment and our latest research for stroke rehabilitation. The technology was demonstrated to clinicians and stroke volunteers. The stroke volunteers' feedback is seen below.

- Want a game that they can use two arms together-all stroke users practiced passive movements/movements with the affected arm by holding with their non-affected arm at home.
- Want a game that will stimulate a reflex reaction to moving their affected arm.
- Make more gameful experiences
- Set up games so that arm can rest on the desk and is able to pick up slow movement which not be smooth and continuous.
- Have a set number of reps
- Have some orientation/instruction/practice at the beginning of each game
- Have a chair with arm rests to orientate the person to maintain position relative to the table/computer as otherwise may rotate towards the affected side.